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GEOLOGICAL MAGAZINE

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The Oslobreen Series, Upper Hecla Hoek of Ny Friesland, Spitsbergen

By D. J. GOBBETT AND C. B. WILSON [1]

(PLATES XIII–XV)

ABSTRACT

Six formations, totalling 1,210 metres and grouped as the Oslobreen Series, are dominantly of dolomite and limestone often with evidence of discontinuous deposition. They contain a Lower Cambrian and a Canadian fauna. The succession is similar to those of this age in N.W. Scotland, where a revised thickness is given, and in E. Greenland. A new species of Canadian trilobite (*Hystricurus*) is described in the Appendix.

I. INTRODUCTION

NY FRIESLAND, part of a Caledonian fold belt, lies in the north of Spitsbergen. Much of the area is ice-covered and the rock exposures are restricted to steep cliffs bordering the glaciers.

The general structure of the Hecla Hoek rocks of this area has been described by Harland (1959). The rocks are metamorphosed in the west but are little altered in the east where they form the eastern limb of a large, north–south trending anticline. The eastern edge of the Hecla Hoek outcrop contains the stratigraphically highest rocks which form a well-defined group of dolomites and limestones known as the Oslobreen Series (Harland and Wilson, 1956). This is bounded below by the shales and tillites of the Polarisbreen Series and above by unconformable Carboniferous strata. The plane of the unconformity dips eastwards and restricts the outcrop of the Oslobreen Series to a narrow, north–south strip somewhat widened by pre-Carboniferous faulting and folding and post-Permian faulting. An east–west section across the area is shown in Text-fig. 3B.

Our present knowledge of the stratigraphy of these Upper Hecla Hoek rocks is due mainly to the field-work of C. B. Wilson. Wilson visited the area in the summers of 1953, 1955, and 1956, and Gobbett in 1958 and 1959.

All the fossils known to have been collected from the Oslobreen Series are in the Sedgwick Museum and have been available in the preparation of this paper. Those collected before 1958 were described

[1] C. B. Wilson met with a fatal accident in Cambridge in May 1959. With characteristic generosity he had previously passed his material relevant to this paper to me, to continue the field work and we had planned to collaborate in publishing the results—D. J. G.

briefly by Hallam (1958). In this paper, preliminary lists of fossils and their Sedgwick Museum numbers are given.

II. Structure (see map, Text-fig. 1)

The Oslobreen Series is well exposed on cliffs in a dozen widely separated localities in the lower parts of Oslobreen and Polarisbreen and on Andromedafjellet. The dip is generally eastwards at 40–50° except on Andromedafjellet where the rocks form a symmetrical north–south syncline. At W139 and W102 the folding is more intense (the beds are overturned towards the west at the latter locality) and accompanied by faulting. The axes of these structures all run approximately north–south.

The unconformity with the overlying Carboniferous beds is well exposed on W139 (see Plate XIV, fig. 1).

The outcrop of Hecla Hoek rocks is interrupted by a wedge of Upper Carboniferous and Permian strata in Oslobreen, bounded by two faults, each with a throw of several hundred metres.

III. Succession

The Oslobreen Series may be divided into the following formations.

Top.	*Maximum thickness.*
Upper Oslobreen Limestone . .	500 metres
Middle Oslobreen Limestone . .	220 metres
Kirtonryggen Dolomite . . .	85 metres
Lower Oslobreen Limestone . .	160 metres
Oslobreen Dolomite . . .	200 metres
Oslobreen Sandstone . . .	45 metres
Total thickness . . .	1,210 metres

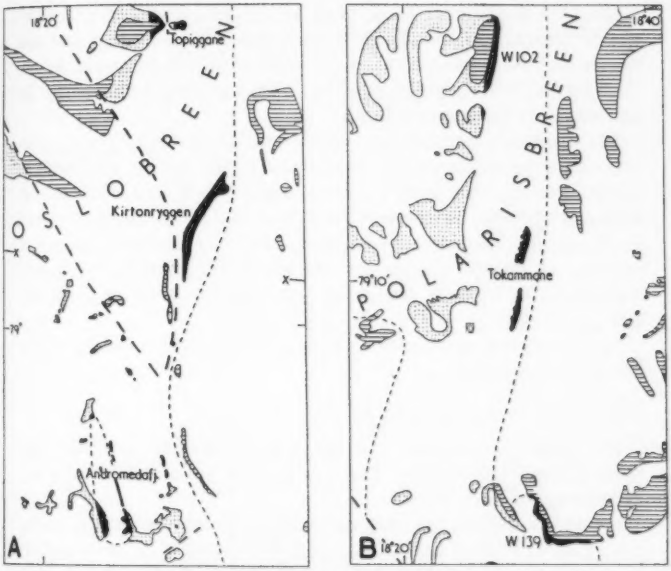
The rocks now named Kirtonryggen [1] Dolomite were previously included in the Lower Oslobreen Limestone. They are separated as a distinct formation since they form a mappable unit and are principally dolomitic. The thicknesses of the three lower formations were measured directly with a tape at their type localities. Those of the upper three were calculated from angular and linear measurements; the thickness of the Upper Oslobreen Limestone is approximate. These thicknesses are a revision of those given by Harland (1959, Table II).

Oslobreen Sandstone (see Text-fig. 2)

The type section of this formation is exposed on south Tokammane. Here it is 45 metres thick and consists of three massive, false-bedded,

[1] The mountain Kirtonryggen is named after C. J. B. Kirton who, in 1958, lost his life while collecting fossils there.

white quartzites (sub-units 1, 4, 6) interbedded with less resistant dark, micaceous, flaggy siltstones and shales with thin, impure, brown-weathering sandstones. The lowermost quartzite rests conformably, but with a sharp junction, on Upper Polarisbreen Shale. The top of the formation is taken at the top of the uppermost quartzite, which is succeeded conformably by Oslobreen Dolomite.



TEXT-FIG. 1.—Geological map of part of Ny Friesland. A. Southern Section. B. Northern Section. Scale: 1:200,000.
Pre-Cambrian Hecla Hoek—dotted, Oslobreen Series—black. Carboniferous and Permian—ruled lines, Faults—thick broken lines. Inferred geological boundaries—fine broken lines. Snow and ice—blank. x——x line of section, Text-fig. 3B.

The quartzite consists of well sorted quartz grains, about 0·2 mm. in diameter, which have been enlarged by secondary growth of quartz in optical continuity. It also contains up to 5 per cent glauconite and sometimes haematite. Both of these minerals tend to be concentrated in layers parallel to the bedding and false bedding. The brown sandstone is poorly sorted (grain size 0·05–2·0 mm.), has a greater percentage of glauconite, contains small amounts of albitic plagioclase and microcline, and much haematite and other, finely divided iron minerals. No carbonates are present. The siltstone is similar in

composition, better sorted (grain size 0·04 mm.), and contains about 15 per cent muscovite.

" Fucoid " markings are abundant in the lower siltstone. At one horizon, 13 metres from the base of the formation, this contains tubes, normal to the bedding (A50690–1). These are about 15 mm. long, circular in cross section, and decrease in diameter from 12 mm. at the upper end to 6 mm. at the lower. They are filled with coarser glauconitic sandstone. These tubes are probably incomplete. They closely resemble *Monocraterion tentaculatum* Torrell as described and figured by Westergård (1931, p. 11, Plates V, VI) from the Lower Cambrian of Västergötland, Sweden. They may have been formed by an annelid worm or a phoronid.

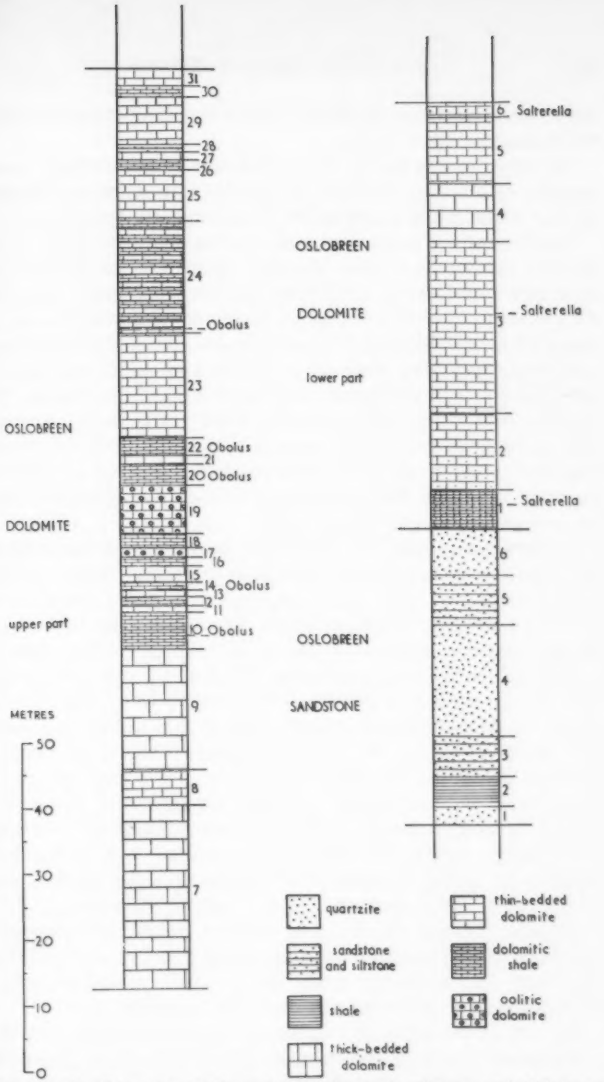
The Oslobreen Sandstone of north Tokammane is very similar to that of the type section. The outcrop at W102 was not examined in detail. The sequence there is disturbed structurally and much of it is obscured by scree. Southwards the formation thins to about 30 metres on Topiggane, 15 metres on Andromedafjellet. At these localities it consists of a massive, glauconitic, white quartzite succeeded by brown-weathering, ferruginous sandstones and siltstones with up to 40 per cent glauconite.

No fossils other than the tubes mentioned above have been found in the Oslobreen Sandstone.

Oslobreen Dolomite (see Text-fig. 2)

On north Tokammane, the Oslobreen Dolomite is completely exposed but is inaccessible. The type sections are therefore taken on Topiggane and Kirtonryggen.

Topiggane displays the lower part of the formation, 65 metres thick, resting on Oslobreen Sandstone. It consists largely of thin-bedded, orange-brown-weathering, dark grey dolomite of silt grade, often brecciated. The basal 5 metres (sub-unit 1, Text-fig. 2) are glauconitic, silty dolomite with abundant " fucoid " markings and ?worm tubes. In thin section this rock shows angular quartz and rare quartzite, small amounts of albitic plagioclase and microcline, about 2 per cent of glauconite and fine shreds of muscovite. These constituents are about 0·05 mm. in diameter and the dolomite matrix contains crystals up to twice this size. Quartz persists into the base of sub-unit 2 and flake conglomerates are common at this level. Sub-unit 3 contains curious, banded dolomites: layers of white dolomite about 1 mm. thick occur at intervals of 2 to 5 mm. in a finer-grained, dark, grey-brown dolomite. Individual layers are approximately parallel to the bedding but cannot be traced far laterally. They are probably a secondary feature related to pseudo-brecciation. Sub-unit 4 is a coarser dolomite with light grey limestone beds. The top of the section (sub-unit 6) is crowded with



TEXT.-FIG. 2.—The type sections of Oslobreen Sandstone and Oslobreen Dolomite, showing main lithologies and fossil horizons.
Oslobreen Sandstone—south Tokammane, Polarisbreen.
Oslobreen Dolomite
lower part—Topiggane, Oslobreen.
upper part—Kirtonryggen, Oslobreen.
Scale 1 : 1,000.

Salterella. This *Salterella* Bed provides a very distinct marker horizon within the Oslobreen Dolomite.

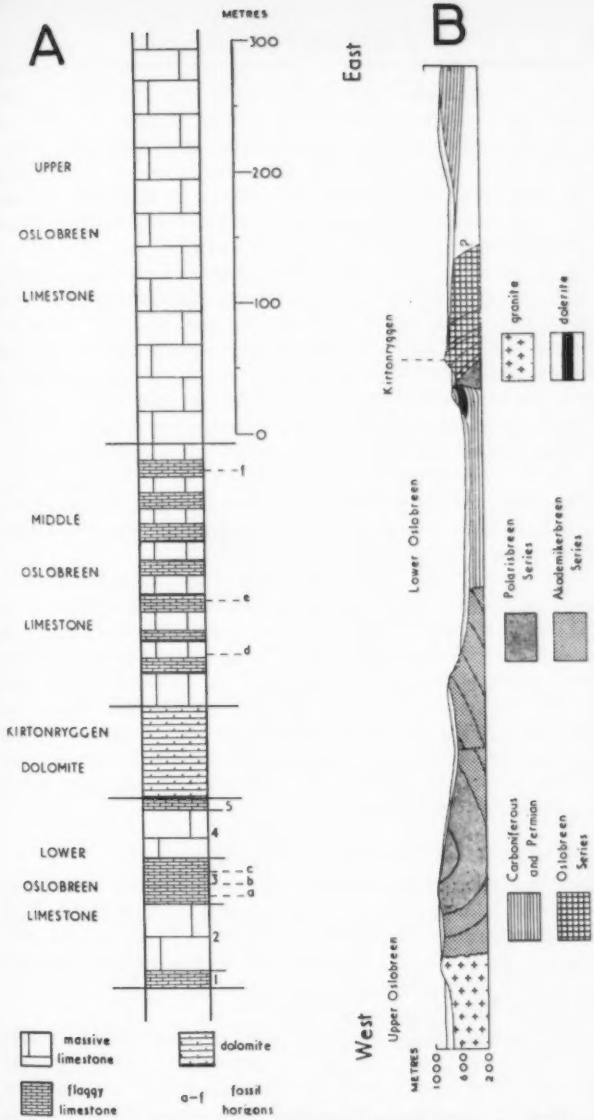
The upper part of the Oslobreen Dolomite on Kirtonryggen is more variable in lithology and may be divided into numerous sub-units, most of which can be traced on W139 and on north Tokammane.

The base of the section lies a few metres above the *Salterella* Bed which is not visible in situ. However, pebbles of the *Salterella* Bed have been found in the scree below the cliff. Sub-units 7 and 9 are thick-bedded dolomite of mud grade (dolomite porcellanite) or silt grade (dolomite siltstone), in places pseudo-brecciated with patches of sand grade (dolomite sandstone). Calcite and chert occur as a fine permeation or in small lenticles and the beds may be brecciated. Thin sections show a small percentage of rounded quartz grains. Recrystallized sub-spherical structures, varying in diameter 0·05–0·5 mm. are commonly present. These may represent the faecal pellets of small mud-ingesting organisms. Sub-unit 8 is of thinner-bedded dolomite siltstone with partings of green dolomitic shale.

At the top of sub-unit 9 is 1 metre of coarse flake conglomerate and above this a very sharp change in lithology to greenish, flaggy, dolomitic shale interbedded with yellow-weathering dolomite siltstone and dolomite sandstone (sub-units 10–16). The dolomite sandstone occurs as thin, irregular layers and lenses, or in irregular patches within the beds of dolomite siltstone, sometimes producing a pseudo-brecciation and, if there are colour differences between the two grades, the rock appears strikingly mottled. Quartz, seen in thin section, has a grain size similar to that of the dolomite crystals (0·025–0·05 mm.). It normally constitutes less than 10 per cent of the rock but may be concentrated in small lenses. A small percentage of glauconite is present in some specimens. The sub-spherical structures mentioned above occur in these dolomites and are also found in the Oslobreen Limestones. At one horizon is 0·25 metres of brown limestone with stromatolites, and at another, a thin dolomitized limestone.

Sub-units 17 and 19 are of a resistant rusty-brown-weathering, pseudo-brecciated dolomite containing clear traces of ooliths in hand specimen. The ooliths are completely recrystallized and can only be distinguished from the matrix by their brown colour.

The rest of the sequence consists of yellow-weathering, pale grey, porcellanous dolomites with flake conglomerates and occasional beds of small stromatolites. These lithologies are interbedded with dolomitic shale. Sub-unit 28 is a medium-grained, brown-weathering, dolomitic sandstone with "fucoid" markings and desiccation cracks on the bedding planes. In thin section it shows a small percentage of plagioclase, microcline, glauconite and muscovite, and about 10 per cent of finely divided iron minerals and ?organic material.



TEXT-FIG. 3.—A. The type section of Lower Oslobreen Limestone, Kirtonryggen Dolomite, Middle Oslobreen Limestone, and Upper Oslobreen Limestone—Kirtonryggen. Lithologies diagrammatic except for Lower Oslobreen Limestone. Scale 1 : 5,000.
B. Horizontal section across Lower Oslobreen. Vertical and horizontal scale 1 : 100,000.

Other sections in the Oslobreen Dolomite differ little from the type sections and the thickness of the formation is constant. The *Salterella* Bed on Andromedafjellet is a recrystallized oolite, containing glauconite. The *Salterella* are partly silicified and weather out on the surface of the rock. The recrystallized oolite found on Kirtonryggen (sub-units 17–19) cannot be traced farther north and sub-unit 28 is absent on W139 but is present on Tokammane North.

The fauna of the lower part of the Oslobreen Dolomite consists of a *Salterella* sp. or spp. cf. *S. rugosa* Billings (see Hallam, 1951 ; also A50695–700) which has been found at two horizons below the *Salterella* Bed (see Text-fig. 2), but not with certainty above it. (Wilson records isolated *Salterella* from 60 metres above the *Salterella* Bed on W139: he collected no specimens and it is possible that they were inorganic structures or that there was some mistake about the horizon as Wilson himself suggested.) This fossil indicates a Lower Cambrian age. Some ?phosphatized fragments (A50692–4) were collected from the base of the formation of north Tokammane. One of these appears to possess a surface ornament of fine granules and may be organic. Another appears to be a fragment of a hyolithid.

The dolomitic shales of the upper part of the Oslobreen Dolomite contain inarticulate brachiopods at several horizons (see Text-fig. 2). These are invariably damaged around the umbo and cannot be generically determined with certainty. Three species may be recognized, one of which is probably a *Lingulella* sp. (A50748). The other two may belong to the genus *Obolus* (see Hallam, 1958; also A50701–47, A50749–61). If these identifications are correct, the age of the beds that contain these fossils may be anywhere between Lower Cambrian and Lower Ordovician, but would most likely belong to the Middle or Upper Cambrian.

Lower Oslobreen Limestone (see Text-fig. 3A)

The type section of this formation and the succeeding three formations of the Oslobreen Series is exposed on Kirtonryggen (see Text-fig. 4). The change in lithology from dolomite to limestone takes place suddenly at the base of the formation, although a few thin limestones are found at the top of the Oslobreen Dolomite.

Three main lithologies may be distinguished.

(*a*) Fine-grained, flaggy limestones with irregular, knobbly bedding planes. These will be referred to as " knobbly flags " in the rest of this paper. They form sub-unit 3 and are interbedded with (*b*) in sub-unit 5.

(*b*) Massive, fine-grained, brown-grey limestones containing veins and patches of coarser, white calcite crystals. This rock contains recrystallized shell fragments, ?algal nodules, ?faecal pellets, and, at some horizons, stromatolites.

TEXT-FIG. 4.—Geological map of Kirtonryggen, 1 : 20,000. The continuous line bounds the cliff face; the broken line is the approximate eastern boundary of the flat top, which is covered partly by rock detritus and partly by snow.

(*c*) Partly dolomitized limestones showing irregular yellow, pink, or red dolomite patches. A striking pink bed occurs near the top of subunit 2. The dolomite is sometimes partly silicified. In thin section these limestones show small amounts of haematite, pyrite, and occasionally quartz.

The thickness of the Lower Oslobreen Limestone (114 metres on Kirtonryggen) increases to 160 metres on W139. Here the sequence is similar but increased amounts of haematite stain some horizons a deep red and pure limestone often shows a pink mottling. The lower half of the formation is exposed on north Tokammane.

Three fossil horizons have been found on Kirtonryggen (see Text-fig. 3A), only the second one on W139 and north Tokammane. Preliminary identification of the fossils is as follows:

Horizon a. *Lecanospira* spp. A (A50762–64) and B (A50765); *Ellesmeroceratidae* gen. and spp. A (50766–70) and B (A50771–6).

Horizon b. Solitary rugose coral gen. and sp. indet. (A50850); *Maclurites* sp. (A50777–8); *Macluritella?* sp. nov. (A50779–87); gastropod gen. and sp. indet. (A50790); cf. *Eoorthis? multicostata* Poulsen (A50791–4); orthid gen. and sp. indet. (A50795); *Hystricurus* sp. nov. see appendix (A50804–38, A50849).

Horizon c. Cystid plates (A50840–48).

For references see Hallam, 1958.

These fossils are of Lower Ordovician (Canadian) age. The rugose coral is of interest, since it may be the earliest one known. It is represented by a single crushed specimen. The trilobite was determined by Hallam as *Hystricurus* aff. *flectimembrus* Ross. More material collected in 1959 shows it to be a new species, which is described in the appendix.

Kirtonryggen Dolomite

This formation abruptly succeeds a prominent flake conglomerate at the top of the Lower Oslobreen Limestone on Kirtonryggen. Here it consists of 70 metres of close-jointed, yellow-weathering, dolomite siltstone interbedded with grey-brown, porcellanous limestone, often partly silicified. The boundary between limestone and dolomite is often highly irregular and occurs within one bed. Flake conglomerate is abundant in the dolomite. The limestones are oolitic at some horizons and often contain stromatolites, especially in the upper half of the formation. These stromatolites differ from those lower in the Oslobreen Series and several forms are present. No other fossils have been found.

In thin sections recrystallized ?faecal pellets are seen in the limestone.

One specimen contains authigenic quartz, idiomorphic, or pseudomorphic after dolomite. The original quartz grain is sometimes outlined by tiny dolomite or calcite crystals.

The Kirtonryggen Dolomite outcrops on W139 where it is 85 metres thick.

Middle Oslobreen Limestone

From the Kirtonryggen Dolomite there is a transition to the massive, grey-brown, cherty limestones forming the base of the Middle Oslobreen Limestone. This formation consists of about 200 metres of massive, grey-brown, crag-forming limestone, interbedded every 1 to 5 metres with " knobbly flags ". Dolomitization is less evident than in the Lower Oslobreen Limestone. The crag limestones are generally recrystallized shelly or oolitic limestones. They contain ?faecal pellets and nodules which are probably algal in origin. Some of the nodules which appear to have escaped recrystallization contain algal filaments similar to those of *Girvanella* (A50914).

The " knobbly flags " are of grey-brown, fine-grained limestone, often with " fucoid " markings, ?worm trails and other trace fossils. Fossils occur at three main horizons in these beds (see Text-fig. 3A). Stromatolites are common in the lower part of the formation. Towards the top, the crag limestones increase in thickness at the expense of the " knobbly flags ".

A preliminary identification of the fauna common to the three horizons is as follows.

> *Helicotoma* sp. A50899–900; Gen. and sp. nov. aff. *Hormatoma* A50901–07; *Archaeorthis* cf. *groenlandica* Poulsen, A50853–63, A50865–73, A50875–78, A50885, A50908–10, A50916–38; *Bolbocephalus* cf. *seeleyi* (Whitfield), A46795; *Bolbocephalus* sp. nov. cranidia, A50880–81, A50932; *?Bolbocephalus* librigenae, A50851, A50883, A50911, A50913, A50935; *?Bolbocephalus* pygidia, A50888–89, A50933–34; *Bathyurina* sp. nov. cranidium, A50890; *?Bathyurina* sp. nov. librigenae, A46796–99, A50886, A50891; *?Bathyurina* sp. nov. pygidia, A50874, A50882, A50884, A50887, A50892, A50894–96, A50936–38, A50941; *Bathyurellus* cf. *tenuis* Poulsen, pygidia, A50940, A50942; Bathyurid dorsal exoskeletons, A50852, A50912; *Hystricurus* sp. pygidia, A50893, A50897; gen. and sp. indet. A. pygidium, A50944; gen. and sp. indet. B. pygidium, A50945; gen. and sp. indet. C. pygidia, A50864, A50879.

This assemblage is Middle to Upper Canadian in age.

The Middle Oslobreen Limestone of W139 is slightly thicker than that of Kirtonryggen but is otherwise similar.

Upper Oslobreen Limestone

The thickness of this formation is probably at least 500 m. The top of the section disappears under the ice-field to the east of Kirtonryggen and the base cannot be clearly defined.

The Upper Oslobreen Limestone is a monotonous series of massive limestones similar to those forming crags in the Middle Oslobreen Limestone. Partial dolomitization commonly occurs in the lower part of the formation and forms a mottled rock. Haematite produces red staining locally. In thin section recrystallized shell fragments and ?faecal pellets are common but in the field recognizable fossils are scarce. They are represented by poorly preserved gastropods, nautiloids and trilobite fragments, which are difficult to extract from the rock.

A small number of fossils may be tentatively designated as follows:

Maclurites sp., A50949–50, A50952; *?Hormatoma* sp., A50946–47; cf. *Straparollina* aff. *holtedahli* Strand, A50948; *?Piloceratidae* gen. and sp. nov., A50953; cf. *Protocycloceras* Hyatt, A59051.

The top 300 metres of the Upper Oslobreen Limestone visible in the field appears to be unfossiliferous.

IV. Discussion

The limestone and dolomite of the Oslobreen Series is largely recrystallized. This is shown by the poor preservation of fossils with a carbonate skeleton and the obliteration of the original structures of ooliths, ?faecal pellets and ?algal nodules. The dolomite occurring in pseudo-brecciated limestone is clearly secondary: that of the Oslobreen Dolomite is secondary at least where the shell of *Salterella* is replaced. Stromatolites frequently occur as limestone and although they may have increased the magnesium content of the sediment, there is no evidence that they enabled dolomite to be deposited. It is reasonable to assume that all these rocks were deposited as limestone and were later partly or wholly dolomitized. A certain amount of silicification, replacing the secondary dolomite, probably resulted from a redistribution of silica already present as quartz grains.

The lack of fossils in the Oslobreen Dolomite other than the thick-shelled *Salterella* and horny brachiopods may be due to the dolomitization rather than to lack of hard parts. In south Spitsbergen Lower Cambrian undolomitized limestone contains a trilobite fauna (Major and Winsnes, 1955).

The Oslobreen Series was probably deposited under shallow water marine conditions on a stable shelf. The unsorted, often coarse textured sandstone and siltstone of the Oslobreen Sandstone indicate close proximity of land. At times strong currents removed the finer material and produced well-sorted, false-bedded orthoquartzite which may be dominant. The glauconite, which has a lower specific gravity than quartz, tended to be concentrated at the surface of each false-bedded unit.

Later the influence of land waned, strong movements of water ceased,

and chemical or biochemical carbonate deposition began. This environment appears to have been a very stable one, lasting from Lower Cambrian to Upper Canadian and probably Middle Ordovician time. The presence of algal structures and occasional oolites indicate a shallow water environment; the flake conglomerate is evidence that emergence and erosion occurred frequently and that sedimentation was discontinuous. This is also shown by the thin-bedded nature of large parts of the succession and the irregularity of bedding planes, e.g. the " knobbly flags ".

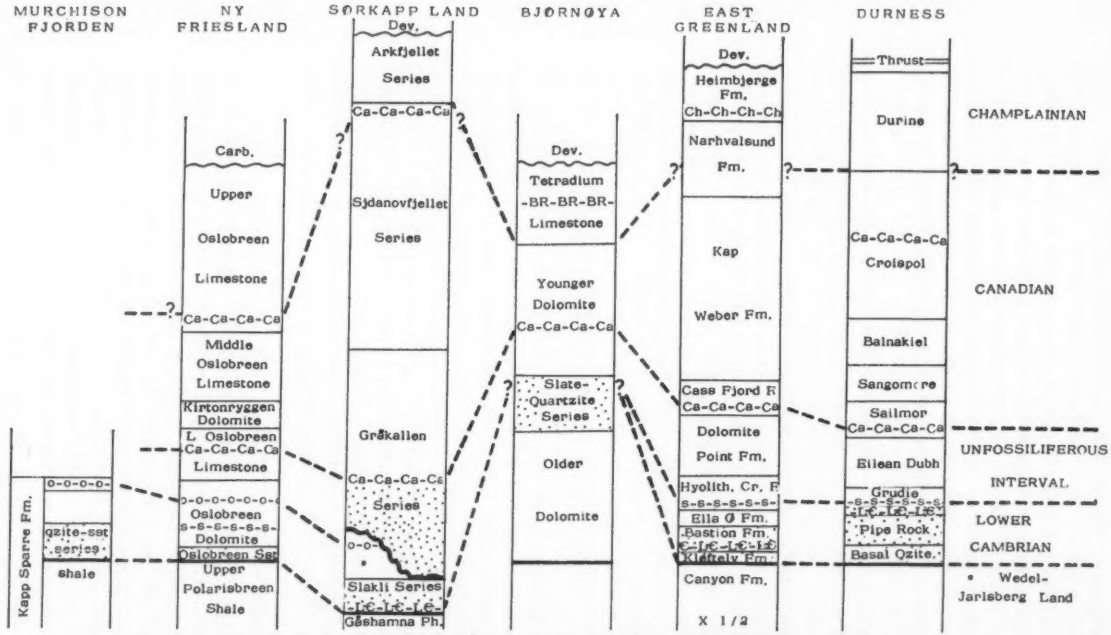
Periods of continuous deposition, probably in less shallow water are now represented in the massive limestones containing a nautiloid fauna, which are particularly developed in the Lower Oslobreen Limestone and the Upper Oslobreen Limestone. The fossils of the " knobbly flags " are benthonic forms (trilobites, orthid brachiopods, and gastropods). Their abundance on certain bedding planes may be explained by sudden emergence and killing of the whole fauna. Normally emergence may have been more gradual or less extensive, enabling at least the free-living animals to escape into pools and tidal creeks.

Correlation with other Areas (see Text-fig. 5)

The Oslobreen Series contains the Lower Cambrian *Salterella* and a Canadian fauna, both of American affinities. In this respect it closely resembles the Cambrian and Lower Ordovician deposits of East Greenland and N.W. Scotland. The lithological sequence in these areas is also similar. Sandstone and quartzite form the base of the succession and are succeeded by a thick sequence of limestones, often dolomitized, beginning in the Lower Cambrian and containing a Canadian fauna but with no proved Middle or Upper Cambrian fossils. Correlation within Svalbard was attempted by Harland and Wilson (1956) and by Harland (MSS).

Nordaustlandet, Spitsbergen

At Kapp Sparre, Murchisonfjorden, inarticulate Brachiopods of *Lingulella* and *Obolus* type are known from the top of a thick succession of Hecla Hoek rocks (Kulling, 1934, p. 188). Kulling's figured specimens (p. 189, fig. 13) resemble our *Obolus* sp. from the Oslobreen Dolomite. The dolomitic mudstones containing the brachiopods lie above grey dolomites which rest on a " quartzite-sandstone series ", probably equivalent to the Oslobreen Sandstone. This sequence represents the upper part of the Kapp Sparre Formation. It is noteworthy that Kapp Sparre lies only 75 km. north of W102 along the strike of the Oslobreen Series.



TEXT-FIG. 5.—Comparative sections of Cambrian and Ordovician rocks.

Murchisonfjorden, Nordaustlandet—after Kulling (1934)
Ny Friesland, Spitsbergen, this paper.
Sørkapp Land, Spitsbergen, after Major, and Winsnes (1955) and Birkenmajer (1958, 1959).
Bjørnøya, after Horn and Orvin (1928)
East Greenland, after Cowie and Adams (1957)
Durness, N.W. Scotland, this paper.
Scale: East Greenland 1 : 40,000, all other sections 1 : 20,000. (200 m. = 1 cm.

Sørkapp Land, Spitsbergen

This area lies at the southern tip of Vestspitsbergen. Here the Hecla Hoek rocks contain Lower Cambrian and Ordovician fossils which were described by Major and Winsnes (1955). The Lower Cambrian fauna includes agnostid and olenellid trilobites but not *Salterella*. It occurs in a thin sandy limestone at the base of the Slakli Series[1] lying above the thick Gåshamna Phyllite which was correlated with the Polarisbreen Series by Harland and Wilson (1956). Barren quartzite and shale separate the Lower Cambrian fauna from a gastropod-cephalopod Canadian fauna in the limestones of the Gråkallen and Sjanovfjellet Series. The highest limestone (Arkfjellet Series) is unfossiliferous.

Wedel Jarlsberg Land, Spitsbergen

Birkenmajer (1958, 1959) recently mapped the Hecla Hoek of this area. His most important discovery was that an angular unconformity exists at the base of the Ordovician (i.e. below the Gråkallen Series of Major and Winsnes, 1955). This break can be traced into Sørkapp Land.

In Wedel Jarlsberg Land, the Slakli Series is followed by 700 metres of dolomites and limestones, the upper part of which (Nordstetinden Series) contains inarticulate brachiopods, as yet undescribed. The Cambrian is intensely folded with the underlying Gåshamna Phyllites. Above the unconformity the Wiederfjellet Quartzites, equivalent to the lower part of the Gråkallen Series of Sørkapp Land, rest on the eroded Nordstetinden and Slakli Series.

Bjornøya, Svalbard

The Canadian age of the Younger Dolomite is well established (Holtedahl, 1920) but no fossils have been found in the Older Dolomite or the Slate Quartzite Series. Holtedahl put these in the Ozarkian, since he considered that all the Hecla Hoek rocks, as then known, were Palaeozoic. Harland and Wilson (1956) and Harland (1959) put them below the base of the Cambrian; if this is correct, Cambrian rocks are absent in Bjornøya. The Tetradium Limestone is the only Hecla Hoek formation of proved Middle Ordovician age. It may be equivalent to the Upper Oslobreen Limestone of Ny Friesland, and the Arkfjellet Series of Sørkapp Land.

East Greenland

The Lower Cambrian fauna of East Greenland includes *Salterella*

[1] In a more recent paper (Birkenmajer 1960. *Report of XXI Session International Geological Congress*, Part 8, pp. 64–74), the Slakli Series was stated to be 150 m. thick and to be underlain by approximately another 150 m. of "lowermost Cambrian" Blåstertoppen Dolomite.

Birkenmajer (1958, 1959).
Scale: East Greenland 1 : 40,000, all other sections 1 : 20,000. (200 m. = 1 cm.
Durness, N.W. Scotland, this paper.
Sørkapp Land, Spitsbergen, after Major, and Winsnes (1955) and

rugosa and trilobites with close affinities to those of the Slakli Series in Sørkapp Land. It is separated from a Lower Canadian fauna by 530 metres of unfossiliferous dolomite.

Durness, Scotland

Salterella is known from the Fucoid Beds, the Serpulite Grit, and the base of the Durness Limestone. These beds are succeeded by some 350 metres of unfossiliferous dolomite before Canadian fossils appear.

The thickness of the Durness Limestone (see Text-fig. 5) measured at its type locality (D.J.G.) was found to be 1,290 metres, over twice that given by Peach and Horne (1907, p. 365) and Phemister (1948, p. 44). Thus the Durness limestone, in its type area is equivalent in thickness to the Cambrian and Ordovician of Svalbard. No angular unconformity is to be seen in the field although erosion surfaces and minor non-sequences are abundant. However Dr. Vernon Wilson (personal communication) has seen evidence of a hiatus between the Grudie and Eilean Dubh groups.

Poulsen (1951) put a hiatus between the Eilean Dubh and the Sailmhor groups. He considered that the fauna of the latter was probably of Upper Canadian age and correlated it with the Kap Weber Formation of East Greenland. The Lower Canadian Cass Fjord Formation was thus not represented in N.W. Scotland.

The lack of a Middle or Upper Cambrian fauna from all these areas suggests that a non-sequence is present although only in South Spitsbergen can an unconformity be seen. It is possible that the inarticulate brachiopods from the Oslobreen Dolomite, the top of the Kapp Sparre Formation, and the top of the Nordstetinden Series, are of Middle or Upper Cambrian age. In East Greenland and N.W. Scotland dolomitization may have destroyed fossils with a carbonate skeleton, originally preserved in Middle and Upper Cambrian deposits.

V. Acknowledgments

This paper is based on the field notes and collections of various members of the Cambridge Spitsbergen expeditions of 1952, 1953, 1955, 1956, 1958, and 1959. Brief accounts of these six expeditions appeared in *The Polar Record* as follows respectively : Bayly, M. B., 1953, vi, 804–5 ; Harland, W. B., 1954, vii, 151 ; 1957, viii, 349 ; Wilson, C. B., 1957, viii, 350 ; Friend, P. F., 1959, ix, 463–4 ; Harland, W. B., 1960, x, 40–44. In particular D. J. G. would like to acknowledge his debt to his companions in the field : R. A. Atherton, J. L. Fortesque, the late C. J. B. Kirton, and M. S. Thornton, and to W. B. Harland, who led the Cambridge Svalbard Expedition, 1959, suggested this paper and advised in preparing it.

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SEDGWICK MUSEUM,
CAMBRIDGE.

APPENDIX

A New Species of Trilobite from the Lower Oslobreen Limestone

By D. J. GOBBETT

Genus *Hystricurus* Raymond, 1913, emend. Ross, 1951

Hystricurus wilsoni sp. nov.

Plate XV, figs. 1–14

Hystricurus aff. *flectimembrus* Ross, Hallam, 1958, p. 72.

Material

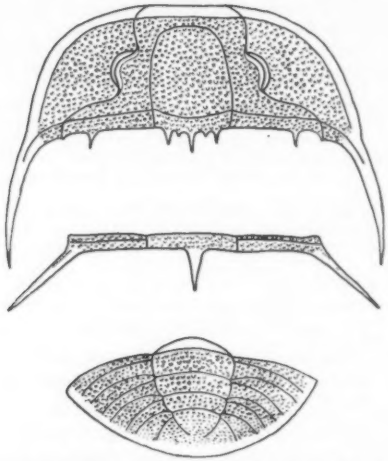
Eighteen cranidia, sixteen free cheeks, six pygidia, and isolated thoracic segments, showing external and internal surfaces, weathered

out on bedding planes of thin-bedded limestone. The fossils were cleaned by brushing the weathered surface with very dilute HCl and washing in water. Latex moulds were made of four specimens.

Holotype: A50804; paratypes: A46782–94, A50805–38, A50849.

Description

No complete specimens of this species have been found, but an attempt to reconstruct the dorsal exoskeleton is shown in Text-fig. 6.



TEXT-FIG. 6.—Reconstruction of *Hystricurus wilsoni* sp. nov.

Surface coarsely pustulose. Cranidium broadly triangular in outline, greatest width lying at posterior margin. Glabella convex, rounded in outline, slightly longer than broad, the sides tapering slightly towards the anterior. Glabellar furrows absent. Occipital furrow deep. Occipital ring bears small stout mesial spine, relatively larger in young specimens, and two lateral spines on each side. Preglabellar field narrow, bordered in front by a smooth rounded ridge. Fixed cheeks with very wide postero-lateral limbs containing deep posterior border furrow. Small spines present on posterior border. Palpebral lobes opposite centre of glabella, bounded by a smooth raised rim, nearly semicircular in young specimens but having greater curvature with recurved extremities in adults. Anterior branch of facial suture slightly divergent but converging towards mid-line over anterior border; posterior branch runs outwards and backwards to the

posterior border furrow, where it turns sharply posteriorly (cf. *H. flectimembrus*).

Free cheeks convex, bearing genal spines diverging slightly from curve of smooth, raised lateral border and approximately equal to it in length. A shallow furrow runs along the proximal side of the base of the genal spine. Eyes borne on narrow crescentic ridges.

Number of thoracic segments unknown. Axis a third as wide as the segment. Interpleural furrows and fulcrum well marked. Pleurae terminating in straight pleural spines. Strong axial spine present in all segments seen.

Pygidium gently convex, greatest width approximately twice length. Axial, pleural, and interpleural furrows well-defined. Four clearly marked axial rings and pleurae. Border narrow and smooth.

Measurements (in mm.)

Specimen	A50812	A50804	A50814	A46783	A50806	A50810	A50809
Length of cranidium	14·0	—	—	—	—	—	3·75
Width of cranidium at posterior border	23·0	26·0	—	c. 13	c. 19	—	7·0
Width of cranidium through centre of palpebral lobes	16·0	14·0	13·0	8·5	c. 10	6·5	4·25
Length of palpebral lobes	5·0	4·5	4·75	2·75	4·75	2·25	1·5
Length of glabella	10·0	8·0	8·0	5·0	7·0	4·25	2·5
Width of glabella at base	8·5	7·25	7·0	4·5	6·0	3·5	2·0

Specimen	A50831	A50833	A50832	A50834
Length of pygidium	6·5	6·0	4·75	6·5
Maximum width of pygidium	15·0	12·5	10·5	14·0

Occurrence

Lower Oslobreen Limestone, 90 metres above the base. A50849 from north Tokammane, Polarisbreen; all other specimens from Kirtonryggen, Oslobreen.

Discussion

The genus *Hystricurus* was revised by Ross (1951, p. 39) who restricted it to species having slender postero-lateral limbs to the fixed cheeks, and palpebral lobes possessing a raised lunate rim and extending posterior to the glabella mid-point. *H. wilsoni* is a large species resembling *H. flectimembrus* Ross in form but differing in its narrower preglabellar field, the absence of pits in the axial furrow of the cranidium, narrower palpebral lobes, and the course of the posterior branch of the facial suture. It is named after C. B. Wilson, co-author of the main part of this paper.

EXPLANATION OF PLATES

PLATE XIII

FIG. 1.—North Tokammane, Polarisbreen, from the West. Cliff length about 1·25 km., height about 80 metres. The continuous line in the Oslobreen Dolomite is drawn at the base of the thinner-bedded sub-units 10–31.

FIG. 2.—Andromedafjellet, Kvitbreen, from the South. Cliff length about 1·7 km., height about 200 metres.

U.P.S. Upper Polarisbreen Shale.
O.S. Oslobreen Sandstone.
O.D. Oslobreen Dolomite.
L.O.L. Lower Oslobreen Limestone.
s. Salterella Bed.

PLATE XIV

FIG. 1.—North end of W139, Oslobreen, from the west showing the sub-Carboniferous unconformity. Distance across photo. at base 1·5 km.; height of cliff about 200 metres.

FIG. 2.—Kirtonryggen, Oslobreen, from the south-west. Cliff length 3·5 km.; height about 150 metres. (Photo. M.S. Thornton.)

U.P.S. Upper Polarisbreen Shale.
O.S. Oslobreen Sandstone.
O.D. Oslobreen Dolomite.
L.O.L. Lower Oslobreen Limestone.
M.O.L. Middle Oslobreen Limestone.
U.O.L. Upper Oslobreen Limestone.
Carb. Carboniferous.

PLATE XV. *Hystricurus wilsoni* sp. nov. × 2.

FIGS. 1–5.—cranidia. 1, Ventral view of the holotype, A50804. 2, Ventral view, A50814. 3, Dorsal view, A46786. 4, Dorsal view, A46783. 5, Slab with two cranidia, A50813 (ventral view) and A50812 (dorsal view).

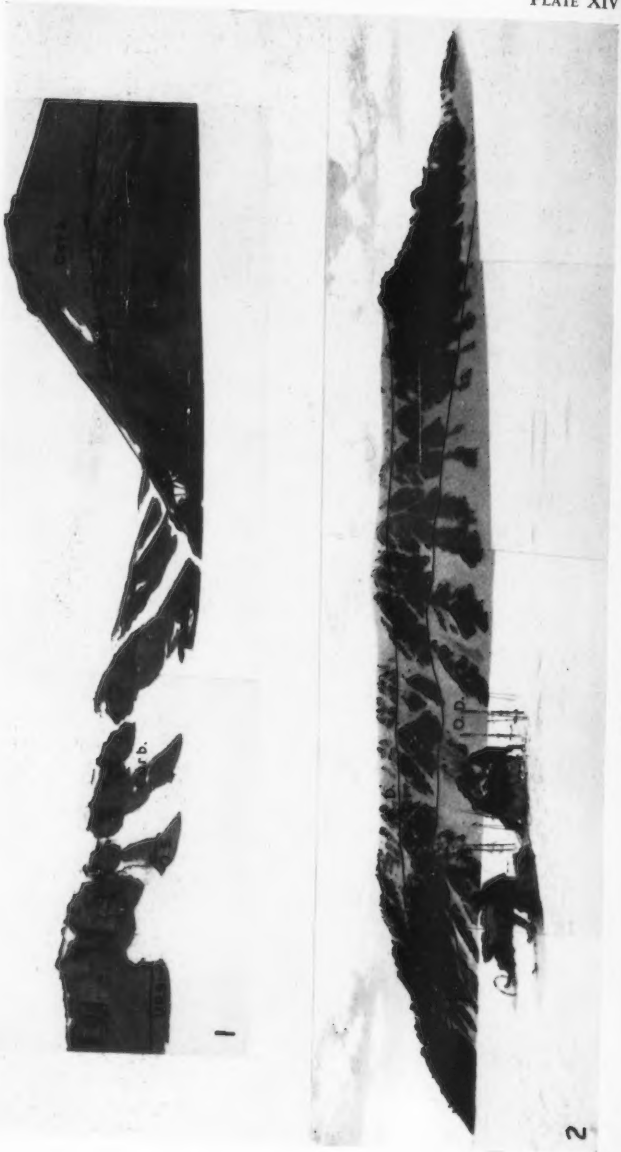
FIGS. 6–9.—Dorsal views of free cheeks. 6, A50818 and A50819. 7, A50850. 8, worn specimen, A50827. 9, worn specimen, A50825.

FIGS. 10–13.—Pygidia. 10, ventral view, A50831. Dorsal view, A50833. 12, Dorsal view, A50832. 13, Dorsal view, A46789.

FIG. 14.—Single thoracic segment, dorsal view, A50836. (Photo. A. Barlow.)

OSLOBREEN SERIES, SPITSBERGEN

facing p. 400



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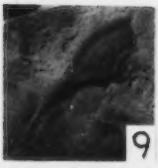


HYSTRICURUS WILSONI sp. nov.

Hornblende Orientation

By F. E. Tocher

Abstract

An ambiguity in previously published hornblende orientation data is pointed out and illustrated by measurements on an epidiorite. A method is proposed of differentiating in certain cases between (*a*) a fabric derived by crystallization of hornblende under stress and (*b*) that derived by alignment of pre-existing hornblende prisms.

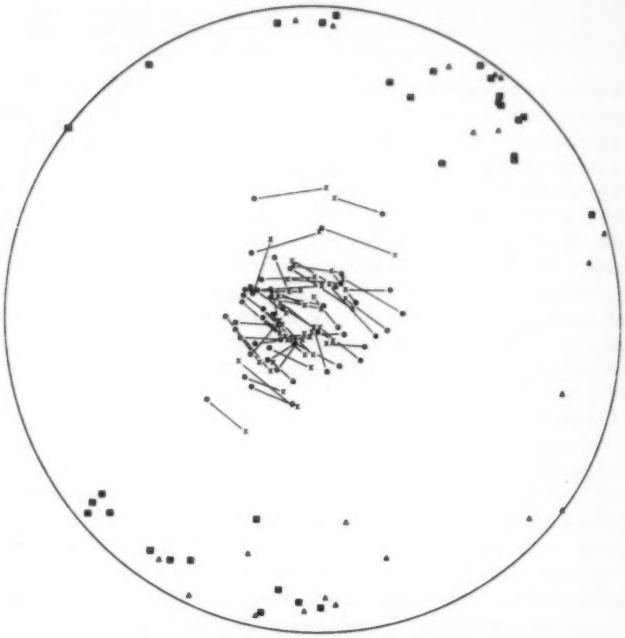
A paper by Schmidt is of interest for its description (1928, pp. 220–2) of an amphibole-zoisite-schist from Rennfeld in which the hornblendes are especially well directed: their crystallographic axes *Z* and *Y* coincide with the rock fabric axes *y* and *x* respectively, where *x*, *y*, *z* of Schmidt (*ibid.*, p. 210) are equivalent to *a*, *b*, *c*, respectively, of Turner (1948, p. 177). Schmidt (*ibid.*, p. 222) concludes from this: "Es haben also die Hornblenden in diesem Gesteine eine durchaus eindeutige Lage". However, the recorded evidence is insufficient to show that the hornblende crystals have an absolutely unambiguous orientation and his conclusions cannot therefore be accepted on the strength of that evidence alone. Despite this discrepancy many standard text-books of petrofabrics (e.g., Fairbairn, 1949, pp. 38, 149; Knopf and Ingerson, 1938, p. 137; Sander, 1930, p. 217; Turner, 1948, pp. 274–5) refer to Schmidt's paper without comment.

On account of the monoclinic symmetry of hornblende the positive and negative ends of its *Y* axis are mirror images of each other and are consequently neither identical nor interchangeable. Despite this, rotation of 180° about the *Z* axis admittedly brings about no obvious change in the attitude of the *Y* or *Z* axes or in the general dimensional orientation of the grain as seen in thin section or in a roughly terminated prism. But from most other aspects there is a considerable difference between the two settings: for instance, the *X* axis, being oblique to the *Z* axis, has, in the two cases, quite different orientations, as have the ellipsoids or other surfaces used to describe all of the continuous properties like optics, elasticity, thermal expansion, etc.

Thus it would seem that Schmidt (*ibid.*) has either (*a*) differentiated between the two possible orientations, but omitted to record the fact, and genuinely observed the existence of only one of them in the rock in question, or (*b*) observed and recorded, without differentiation, both orientations within the same rock. Be that as it may, it is felt that the ambiguity of the recorded information should be brought to light and the position clarified; for in the second alternative Schmidt's conclusion would obviously be false.

A specimen of puckered, schistose and lineated epidiorite from the Geallaig Hill, 700 yards W. 25° N. of Dalbagie, near Ballater, West

Aberdeenshire, will serve to illustrate the ambiguity. A thin section, cut perpendicular to the lineation, showed, within the planar portion of the limbs of adjacent small folds, conditions similar to those recorded by Schmidt : prism axes, defining the lineation, almost parallel, and Y axes almost constant in direction in the plane of schistosity. Using a

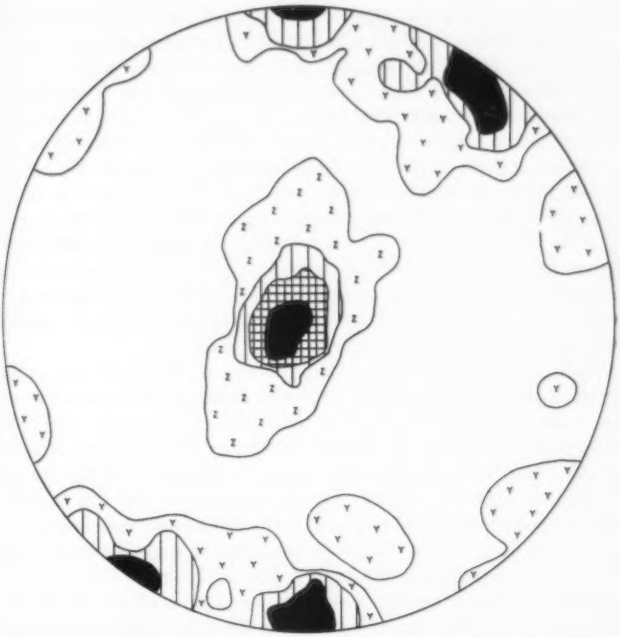


TEXT-FIG. 1.—50 hornblendes showing Z axes (crosses), + Y axes (squares), − Y axes (triangles), optical vibration direction γ (circles), and general orientation of optic axial plane (straight lines).

5-axis universal stage, the orientations of the Z axis, the optical vibration direction γ, and the Y axis, positive or negative as the case may be, of 50 hornblende crystals were determined and plotted on the lower hemisphere using the Schmidt net (Text-fig. 1). The Y axis was plotted as the pole of the optic axial plane, defined in the projection by Z and γ, and its sign, + ve or − ve, deduced from the known optical orientation of hornblende ; whether the plotted end of the Z axis be regarded as + ve or − ve makes no difference in this connection.

Both the possible orientations of hornblende, related by rotation of

180° about *Z*, are represented (in the approximate ratio 60 : 40), thus demonstrating that, although the crystallographic axes *Z* and *Y* of this mineral appear to be so strictly limited in orientation within a rock, the prismatic crystals have not necessarily " eine durchaus eindeutige Lage ". When only these two directions, *Z* and *Y*, are plotted, the



TEXT-FIG. 2.—Distribution of *Z* axes, maximum 38 per cent (in centre) and *Y* axes (undifferentiated), maximum 16 per cent (around periphery) as in Text-fig. 1.

latter without differentiation of positive and negative ends, the resulting contoured diagram (Text-fig. 2) compares favourably with those of Schmidt (*ibid.*, p. 220).

In the interpretation of the structures of hornblende-bearing directed rocks in which both $\pm Z$ and $\pm Y$ of the hornblende are rigidly orientated with respect to the fabric axes (not necessarily exactly as in the case outlined by Schmidt (*ibid.*, pp. 220–2)) the recognition of the possible existence of two distinct orientations may be of great importance : the preponderance of any one orientation in such a rock,

in whole or in part, would suggest something other than grain-shape as the determining factor in the production of the preferred orientation. If the orienting forces are to be regarded as acting upon already formed prismatic hornblende crystals then it is reasonable to expect that the rudely terminated prisms would, as geometrical solid bodies, present orthorhombic characteristics and that no differentiation would be made between the positive and negative ends of the *Y* axis : both orientations would then tend to be found with equal frequency regardless of whether the symmetry of the deforming forces were monoclinic or orthorhombic. If, on the other hand, the crystals were generated and developed under the influence of the deforming forces, it is credible that the distribution of hornblende prisms between the two orientations would reflect the symmetry of those forces (Knopf and Ingerson, 1938, pp. 44–62, 122–5 ; Sander, 1930, pp. 144–6 ; Turner, 1948, pp. 188–92) : that one of the two orientations would predominate or exist alone if the distribution of forces is monoclinic ; that both would be equally possible if the forces show orthorhombic symmetry. This assumption may be justified provided that no critical component of those properties of hornblende responsible for its orientation in this manner is sensibly perpendicular to the prism axis in the *XZ* plane.

With these considerations in mind there may be, in the case of the rocks specified and where the movements responsible for the fabric can be shown to be monoclinic in character, a possible method of distinguishing between (*a*) a fabric derived by crystallization of hornblende under stress and (*b*) that derived by alignment of pre-existing hornblende crystals. In case (*a*) one orientation may predominate (the planes of symmetry of both mineral and movement may be expected to coincide and, although not a necessary requirement, the hornblende *Z* axes may coincide with the *a* fabric axis, cf. Schmidt, 1928, p. 222) ; in case (*b*) both orientations may be equally possible. Where the forces are orthorhombic in distribution both orientations would be equally possible in each case.

And conversely, where the preponderance of one orientation is demonstrated (the ratio 60 : 40 in the 50 Geallaig Hill grains, above, is insufficiently high to be regarded as a preponderance) it should be strong evidence in favour of a monoclinic distribution of deforming forces, with the *ac* fabric plane defined by the *XZ* symmetry plane of the hornblende.

I am indebted to Dr. M. Munro of this Department for reading the manuscript and for making valuable criticisms and suggestions.

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Metamorphism of the Jurassic Rocks of Glas Bheinn Bheag, near Dunan, Isle of Skye

By Shelagh M. Smith

(PLATE XVI)

Abstract

A succession of Jurassic sediments is shown to have been metamorphosed in contact with a Tertiary microgranite. The metamorphic features of the three main lithological groups of the sediments are described and the conclusion is reached that in addition to simple thermal metamorphism, which is apparent in most of the rocks, the rocks nearest the microgranite have been permeated by aqueous fluids containing K_2O, Na_2O, MgO, FeO and Fe_2O_3.

I. Introduction

Dunan is a village in central Skye, situated on the coast some five miles north-west of Broadford on the road from there to Portree. The area around and to the south of Dunan was mapped on the scale of six inches to one mile in the summer of 1955. This area is chiefly occupied by the hill Glas Bheinn Bheag, about 1,100 feet high, the summit and eastern flank of which are composed of Jurassic sediments—hornfelses, indurated feldspathic sandstones, calcareous quartzites, and mudstones—which dip at a moderate angle to the south-east. These rocks are metamorphosed in the vicinity of Tertiary microgranite which underlies them and forms the western side of the hill. The Jurassic rocks continue to the northern end of Glas Bheinn Bheag, where they are cut off abruptly by a fault (the Dunan fault) striking west-south-westwards from the shore through the village and across the lower ground to the north of the hill. To the north of this fault is granophyre. All the rocks, the sediments in particular, are cut by numerous acidic sheets and sills, and also basic dykes, none of which are described or discussed in this paper.

Central Skye was first mapped in detail by the Geological Survey of Scotland (Harker, 1904, Peach and Horne, *inter alia*, 1910). The geological interest of the Dunan area was revealed by Day (1931) who described the contact of the granite or granophyre with Jurassic sandstones at Dunan, suggesting that the contact was of normal intrusive type. This contact was re-examined and re-interpreted by Black (1955) who showed that the junction is a fault. The present author, from work upon the Jurassic sediments in the Glas Bheinn Bheag-Dunan area, has been able to distinguish six metamorphic zones present in these rocks and can thus add to Black's work by showing that a small thickness of the Jurassic rocks has been cut out by the Dunan fault. These rocks, of the highest grades of metamorphism, appear to be represented in the fault breccia in a more important manner than that envisaged by Black.

II. Field Relations

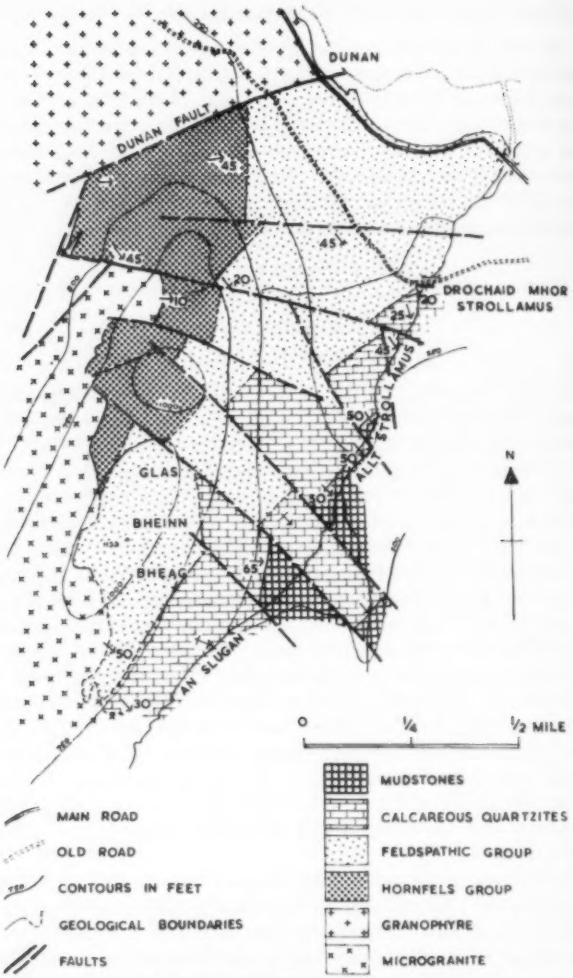
As may be seen from the map (Text-fig. 1) the Jurassic sediments occupy the summit and eastern flank of Glas Bheinn Bheag and extend from Dunan as far southwards as the head of An Slugan. The strata dip south-eastwards and the angle of inclination, low to moderate in the north and west, increases eastwards and is about 50° where the rocks are exposed in the beds of An Slugan and the Allt Strollamus. The sediments are about 2,000 feet thick and may be divided on lithological grounds into four stratigraphic units:

(4) Mudstones
(3) Calcareous Quartzites
(2) Feldspathic Group
(1) Hornfels Group

The rocks comprising the three lower groups have been assigned to the Inferior Oolite series, while the Mudstones have been considered to belong to the Great Estuarine Series (Peach and Horne, *inter alia*, 1910).

The lowest beds exposed form the Hornfels Group: their maximum observed thickness is 700 feet. They occur in the north-western part of the area on the northern and western slopes of Glas Bheinn Bheag, but are cut out by the microgranite towards the south. Small bodies of hornfels occur within the microgranite below the main contact line of the microgranite with the sediments. Succeeding the Hornfels Group is a thickness of 350 feet of rocks composing the Feldspathic Group. This group forms the summit and the upper part of the eastern side of the hill, and passes upwards into the Calcareous Quartzites. This succession is 650 feet thick and consists of quartzites with calcareous lenses and doggers which become more abundant in the higher strata. The Calcareous Quartzites are exposed near the head of An Slugan and on the lower part of the eastern side of Glas Bheinn Bheag. The Mudstones, which are of unknown thickness, follow upon the Calcareous Quartzites and are found in the bed of the upper part of the Allt Strollamus.

Tertiary microgranite occupies most of the western side of Glas Bheinn Bheag. Stream sections and intermittent exposures along the western side of the ridge reveal that the microgranite passes below the sediments. The contact strikes approximately north-south along much of its length, nearly parallel to the strike of the sediments, but in the south the junction trends eastwards and crosses the ridge from west to east, while in the north it has been displaced a quarter of a mile towards the west by an east-west fault. Granophyre, also of Tertiary age, occurs in the extreme north of the area, cut off from the sediments by the Dunan fault.



TEXT-FIG. 1.—Map of Glas Bheinn Bheag showing the distribution of the lithological groups of the Jurassic sediments.

Normal faults, of variable strike and throw, occur on Glas Bheinn Bheag, but are of little importance compared with the Dunan fault. This fault appears to be nearly vertical and is a normal fault with the downthrow towards the south.

III. Petrography of the Jurassic Sediments

The petrography of the Jurassic sedimentary rocks of Glas Bheinn Bheag is complicated since these rocks may be divided on the basis of their petrography in two ways. Either they may be represented in the four lithological divisions which are easily recognizable in the field, or they may be described on the basis of the six arbitrary metamorphic zones which have been discovered as the result of laboratory work. Thus the detailed petrographic features of these zones are described below in relation to the lithological groups of the sediments.

The chief features of the metamorphic zones are as follows:

Zone 1.—The sediments contain a large amount of groundmass, and less recrystallized material than original detrital material.

Zone 2.—Compared with zone 1, considerable recrystallization and alteration of the feldspars have taken place so that the percentage of new-formed feldspar is greater than that of original feldspar.

Zone 3.—In this zone much of the quartz and feldspar has recrystallized, while the amount of new-formed alkali feldspar has increased.

Zone 4.—All the quartz and feldspar have recrystallized. The transition from zone 3 to zone 4 is extremely gradual.

Zone 5.—The increase in the amount of biotite and iron ore minerals (in the case of the Calcareous Quartzites, diopside, epidote and garnet) over that occurring in the previous zone is marked.

Zone 6.—This zone is characterized by the presence of feldspar porphyroblasts, a marked increase in the feldspar and dark minerals, and a proportional reduction in the amount of quartz.

A significant feature of all the metamorphosed sediments of Glas Bheinn Bheag is that whereas the original quartz consists of subangular or rounded grains exhibiting shadow extinction, the new-formed quartz occurs in rounded mosaic aggregates or as discrete equidimensional crystals, the latter generally occurring where the percentage of quartz is either extremely low or unusually high. The original feldspar also occurs as subangular or rounded grains which are generally clear, whereas the new-formed feldspar is, in the lower grades of metamorphism, cloudy and may rim original feldspar. In the higher grades, however, the new-formed feldspar exhibits a progressive decrease in cloudiness.

A. *Hornfels Group.*—These rocks are metamorphosed impure sandstones, medium to fine-grained and generally dark in colour. Subangular grains of quartz with subordinate orthoclase, microcline and oligoclase, lie in a matrix of chloritic, feldspathic and sericitic material. Ilmenite

and magnetite are present in variable quantity, and accessory minerals include apatite, zircon, sphene, brookite, tourmaline and garnet. Zones 2, 3, 4, 5 and 6 are present.

Zone 2.—The rock consists of subangular grains of strained quartz, sparse aggregates of mosaic quartz and a subordinate amount of rounded feldspars, in a groundmass composed of chlorite and sericite together with cloudy irregular masses of new-formed feldspar, some of which have diffuse margins. Accessory minerals are also present.

Zone 3.—Only a small proportion of the quartz grains are unaltered: the bulk of the quartz consists of subangular aggregates of mosaic crystals set in a matrix of cloudy (chiefly recrystallized) feldspar together with a little chlorite and accessory minerals.

Zone 4.—The rock is distinctly banded, due to accumulations of new-formed dark minerals (biotite, chlorite, ilmenite and magnetite) along bedding laminae of heavy minerals, chiefly zircon and sphene. The quartz and feldspar are totally recrystallized and the latter is less cloudy than in zone 3, and identified as alkali feldspar. The groundmass is chiefly composed of biotite, either foxy-red where it rims magnetite, or more commonly greenish in colour with dark pleochroic haloes; it has apparently formed by the alteration of clots of green chlorite.

Zone 5.—The rock differs from that of zone 4 in that it contains a larger amount of feldspar, chlorite, biotite and magnetite. Much of the feldspar is clear alkali feldspar.

Zone 6.—The rock of zone 6 is very dark coloured, almost black, and granulitic in texture. It contains much feldspar, both interstitial cloudy sericitized feldspar and clear anhedral porphyroblasts of orthoclase, oligoclase and also microperthite. A subordinate number of lake-like porphyroblasts of quartz are also present. These contain small inclusion of feldspars, quartz and ferromagnesian minerals. The matrix of the rock consists of equant grains of quartz and feldspar together with much bright green chlorite and tabular almost colourless biotite. Apatite is also present. The hornfels grades into the microgranite through a transition zone one to six inches wide in which the rock is strongly banded, light bands consisting almost entirely of porphyroblastic feldspar with interstitial micropegmatite, and dark bands containing a similarly high proportion of biotite, chlorite, ilmenite and magnetite, together with hornblende, of sparse but significant occurrence.

From the above description and Table I it can be seen that in the Hornfels Group the most marked changes from zone 2 to zone 6 are the increase in the amount of feldspar and dark minerals, and the corresponding decrease in the amount of quartz. There is also a reduction in the amount of groundmass and the development of porphyroblasts in the area of contact with the microgranite (zone 6). Although zone 6

is very narrow, the change in the rock is continued right up to the contact.

TABLE I.

	Zone 2	*Zone 3*	*Zone 4*	*Zone 5*	*Zone 6*
Original quartz . . .	48·5	1·0	—	—	—
Recrystallized quartz . .	11·5	38·5	50·0	41·5	11·0
Original feldspar . . .	10·0	5·0	—	—	—
Recrystallized feldspar . .	16·0	22·5	33·5	40·5	61·0
Biotite and chlorite . .	2·0	7·0	8·0	9·0	22·0
Iron ore (and accessories) .	1·5	1·5	2·5	5·0	6·0
Groundmass . . .	10·5	24·5	6·0	4·0	—
	100·0	100·0	100·0	100·0	100·0

Table of average modal analyses of rocks of metamorphic zones 2, 3, 4, 5 and 6 : Hornfels Group. The changes in mineral proportion are considered to be metamorphic features, as the collection of a considerable number of specimens from throughout the Hornfels Group is regarded as sufficiently random to outweigh the minor lithological variations which undoubtedly are present.

B. *Feldspathic Group.*—The feldspathic rocks are coarser in grain than the hornfelses. Most rocks of the Feldspathic Group are evenly medium or coarse-grained, but gritty bands are also present. The rocks are generally white or pale bluish grey in colour and consist of rounded and angular grains of quartz and feldspar set in a groundmass of sericite and chlorite. The feldspars are orthoclase, microcline, albite and more calcic plagioclase, together with a little microperthite. Ilmenite is the most abundant iron ore mineral, but magnetite is also ubiquitous. Accessory minerals are rare and comprise muscovite, zircon and sphene. Zones 1, 2, 3, 4, 5 and 6 are present.

Zone 1 (Plate XVI, Fig. 1).—The rock consists of subangular and rounded grains of strained quartz, rounded grains of orthoclase, oligoclase, microcline and microperthite. Some of the oligoclase contains flakes of sericite. The groundmass consists of blebs of pale green chlorite and irregular clumps of ilmenite lying in a sericitic matrix.

Zone 2 (Plate XVI, Fig. 2).—The strained quartz grains are in some cases broken up into mosaic aggregates within the original grain boundaries. Much of the feldspar is cloudy, and the new-formed cloudy feldspar rims and partially replaces the original feldspar. The percentage of groundmass material is less than in the rocks of zone 1.

Zone 3 (Plate XVI, Fig. 3).—The rock shows an incipient development of granulitic texture. The feldspars are cloudy and granular, the original ones having partially lost their original outlines. Most of the quartz is in the form of small mosaic grains, and sparse micropegmatite is present interstitially. Pale greenish brown biotite occurs as needles and flakes, often with pleochroic haloes. The groundmass is sparse and consists of sericite and chlorite.

Zone 4 (Plate XVI, Fig. 4).—The rock is finer in grain than that of zone 3, and is composed largely of mosaic quartz and granular feldspar. The iron ores occur as rims around the heavy minerals, and in laminae associated with biotite.

Zones 5 and 6 (Plate XVI, Figs. 5 and 6).—Compared with zone 4, these zones contain a greater amount of feldspar, much of which is porphyroblastic.

The changes in mineral composition of the Feldspathic Group are not so marked as in the case of the Hornfels Group, and are essentially a gradual increase in the amount of feldspar and a marked drop in the proportion of quartz in zone 6.

C. *Calcareous Quartzites.*—The calcareous rocks are generally coarse in grain and white in colour. Poorly preserved fossils are present at some horizons. The rocks consist of subangular grains of quartz in a groundmass of calcareous material comprising calcite and wollastonite, together with lesser amounts of diopside, epidote and garnet. Ilmenite, pyrite and haematite are of very sparse occurrence. Zones 2, 3, 4 and 5 are considered to be present.

Zone 2.—The rocks of this zone have unfortunately been collected only from the lowest beds, and, therefore, unlike the more typical members of the Calcareous Quartzites, contain feldspar as well as calcareous material and quartz. The rock is medium to coarse-grained, consisting of subangular grains of quartz, some of which exhibit shadow extinction, while a few are broken up into mosaic aggregates. Rounded grains of detrital feldspar, chiefly cloudy orthoclase, together with clear microcline and oligoclase, are also present. The groundmass consists of greenish biotite, chlorite, ilmenite, calcite and sericite, and in addition wollastonite, the only calc-silicate mineral found in this zone.

Zones 3 and 4.—More typically calcareous rocks occur in these zones. They consist of 60 per cent to 80 per cent quartz, which is largely in the form of mosaic aggregates, in a groundmass of calcite and a little argillaceous material together with calc-silicate minerals. Wollastonite is the most abundant of these, comprising up to 20 per cent of the rock. It occurs interstitially, either as fibrous masses or as twinned subhedral crystals, or as rims of radial fibres surrounding and penetrating quartz crystals. Some of the calcite is an alteration product of wollastonite, but it is often difficult to determine whether much of it is of primary or late origin. Diopside and grossularite occur sparsely as small idiomorphic crystals at the margins of, and included within, large crystals of primary calcite.

Zone 5.—In the more quartzose varieties of the Calcareous Quartzites of this zone, the quartz occurs only as mosaic aggregates, and wollastonite is absent. Dark minerals are, however, scattered in small

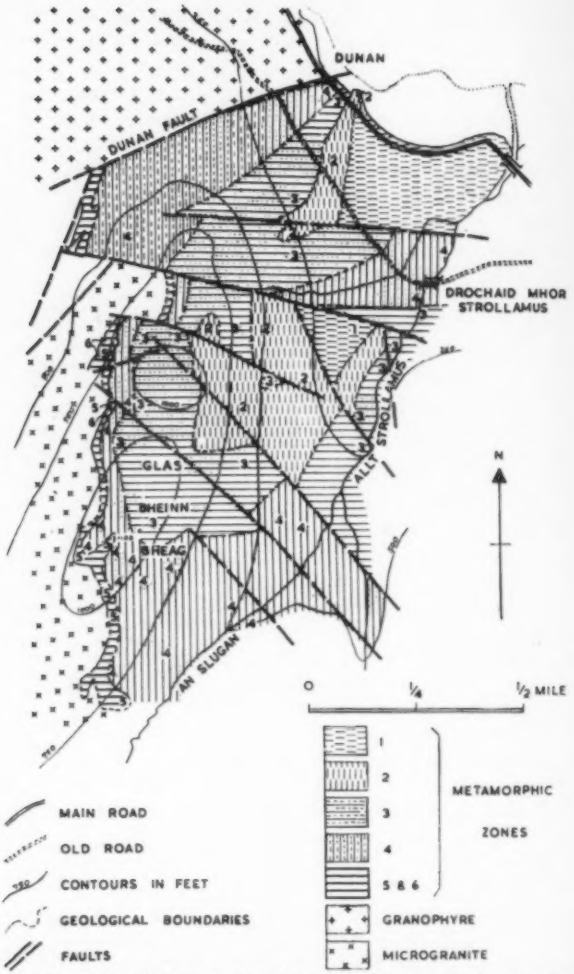
clumps throughout the rock. In those rocks containing a lesser amount of quartz, the grains of this mineral are separated from one another by a mass of fibrous wollastonite and granular diopside, epidote and garnet. The quantity of wollastonite does not generally exceed that of the dark minerals. Calcite is ubiquitous but is invariably an alteration product of wollastonite.

Thus it can be seen that in the Calcareous Quartzites increasing metamorphic grade is revealed by change in character of the quartz, decrease in the amount of wollastonite and increase in the quantities of diopside, epidote and garnet.

D. *Mudstones.*—The usual colour of the mudstones is black or dark bluish grey streaked with red and orange. Some parts of the Mudstones are massive, but most are finely laminated. Calcareous parts contain a shelly fauna. The extremely fine-grained nature of the rock has rendered work on the metamorphism of these rocks impracticable.

By use of the point counter, and by microscope analysis, the metamorphic zone of each specimen of sediment, other than mudstone, has been determined. The localities of these specimens were plotted on the map of Glas Bheinn Bheag, and from these a map showing the approximate distribution of the metamorphic zones was compiled. Text-fig. 2 shows the field relations of the zones and a number of point-plots. The rational distribution of the arbitrarily determined metamorphic zones suggests that the characters upon which the determination was based are significant. Approximate thicknesses of the zones have been obtained by means of stratum contouring.

It can be seen from the map (Text-fig. 2) that zone 1, which is of unknown thickness, occurs at the extreme north-eastern end of Glas Bheinn Bheag, and also in a small area on the eastern flank of the hill, about 500 yards south-west of the bridge over the Allt Strollamus at Drochaid Mhor Strollamus. Zone 2 is about 100 feet thick and extends from the coast at Dunan southwards up the eastern side of the hill to some distance above the old road. A larger tract of country occupied by this zone is an irregular area nearly half a mile long and of similar width, which occurs on the eastern side of the ridge about half a mile to the north-west of the summit. Zone 3, about 200 feet thick, is more widespread. It extends southwards from Dunan more or less along the crest of the ridge almost as far as the summit, and partially encloses zone 2, reappearing in an eastern strip in the Allt Strollamus area. Zone 4 is of much the same thickness as zone 3 and also occupies a large area. It occurs in the low ground to the south-west of Dunan, and extends in a fairly narrow strip southwards along the western side of the hill. It is found at the summit and on the whole of the south-eastern flank and in the bed of An Slugan. It also occurs to the north-east, around Drochaid Mhor Strollamus. Zone 5 is rather narrow,



TEXT-FIG. 2.—Map of Glas Bheinn Bheag showing the distribution of the metamorphic zones in the Jurassic sediments.

perhaps 50 feet thick, and zone 6 is only a few feet thick. These two zones occur together, zone 5 overlying zone 6, on the western side of Glas Bheinn Bheag along the contact with the microgranite. Zone 5 is also present at Dunan against the Dunan fault.

IV. Petrography of the Tertiary Microgranite and Granophyre

As the petrogenesis of these rocks is not under discussion in this paper, only a brief summary of the chief petrographic features is made here.

A. *Microgranite.*—Although the textural and mineralogical composition of the microgranite is variable, three main types may be distinguished, namely micrographic microgranite, granular microgranite and spherulitic microgranite. The first of these is the commonest type. Granular microgranite is found only in the contact areas against the sediments where it is ubiquitous, while spherulitic microgranite is of sparse and irregular distribution. The micrographic microgranite is a medium-grained pale coloured rock containing a large proportion of micropegmatite, here quartz intergrown with alkali feldspar and/or oligoclase, which occurs interstitially and also rims large crystals of plagioclase. Quartz, oligoclase, orthoclase, microperthite and albite are also common in the micrographic microgranite, while augite, hornblende, biotite and chlorite together rarely exceed 8 per cent of the rock volume. Accessory minerals include haematite, ilmenite, zircon, sphene, epidote, orthite and apatite. The granular microgranite differs from the micrographic microgranite chiefly in its granular texture. The groundmass contains a higher percentage of quartz and oligoclase. The dominant ferromagnesian mineral is brownish-green hornblende rather than augite, and among the accessory minerals pyrite is present but orthite has not been found. The difference between the spherulitic and micrographic microgranites is merely one of textural variation. The micropegmatite of the spherulitic rock is very fine-grained and most of it has a feathery appearance.

B. *Granophyre.*—The granophyre north of the Dunan fault is medium to coarse-grained and is as variable in texture as the Glas Bheinn Bheag microgranite. In some areas, especially in the immediate vicinity of the Dunan fault at Dunan, the rock is so granular that it could be termed a granite. At one locality on the shore at Dunan a beautifully coarse spherulitic variety is present. The true granophyric rock is dominant, however. The constituent minerals are quartz, microperthite, orthoclase, oligoclase, albite, biotite, hornblende, magnetite, pyrite and haematite together with accessory sphene, epidote, clinozoisite, orthite, tourmaline, apatite, and zircon. The dark and accessory minerals are not abundant and rarely comprise more than 8 per cent of the total volume of the rock.

V. Discussion

The induration and metamorphism of the Jurassic sediments were alluded to by Flett in the Glenelg Memoir (Peach and Horne, *inter alia*,

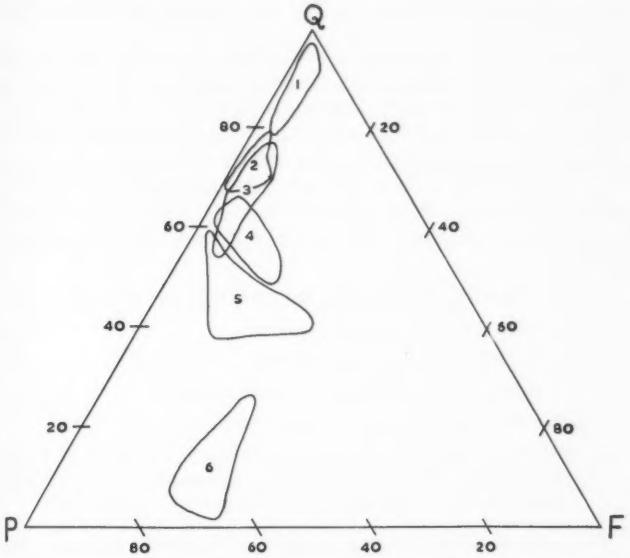
1910, p. 120), who described " a sliced specimen [of the Hornfels Group] as baked feldspathic sandstone, undoubtedly indurated and rendered more compact by thermal action but showing few mineral changes ". The alteration of the calcareous beds to " white sandy marble amongst altered sandstones " was also mentioned.

Field and petrographic evidence, in particular the cutting of the sediments by the microgranite and the increase in grade of metamorphism towards the microgranite, demonstrate that the sediments have been metamorphosed at the time of, and in connection with, the emplacement of the microgranite. The change in the sediments is from rocks composed largely of rounded detrital grains set in a fine-grained groundmass, to more granulitic rocks consisting of porphyroblasts of feldspar set in a matrix of equant grains of quartz, feldspar and ferromagnesian minerals, or, in the case of the Calcareous Quartzites, to granular quartz together with calc-silicate minerals. This, in addition to the complete absence of cataclasis or other dynamic alteration, indicates that the operative metamorphic process was indeed one of thermal activity.

Accompanying the textural change, the sediments exhibit changes in mineral proportion which are especially marked in the Hornfels Group but less so in the Feldspathic Group and the Calcareous Quartzites. Text-fig. 3 is a triangular diagram illustrating the passage from quartz-rich rocks to those rich in feldspars and basic minerals as demonstrated by the two former groups. The modal analyses of the sediments give at best only an indication of their chemical composition, but it seems beyond doubt that, as the changes in mineral proportion are so significant, these reflect chemical changes in the rock. Examination of a set of modal analyses (Table 1) indicates that chemical readjustments without metasomatism may have been responsible for the marked drop in the percentage of groundmass in the middle zones: the sharp increase in the amounts of feldspar and dark minerals in the higher grades, however, is so great that these minerals cannot be regarded as having developed solely from the groundmass, and it appears that the sediments have undergone chemical change (metasomatism). The increase in the amount of feldspar from 26 per cent to 61 per cent is largely due to the development of alkali feldspar, and as most of the increase has occurred in the highest grade (zone 6) it seems likely that K_2O and Na_2O have been introduced. The sudden increase in the amounts of biotite, chlorite and iron ore minerals, initiated in zone 5 and marked in zone 6, suggests that there has also been some introduction of MgO, FeO, Fe_2O_3 and OH.

In the Calcareous Quartzites a similar phenomenon has been detected. Whereas the chief change in the lower zones is the formation of wollastonite and dark minerals from groundmass material, in zone 5

diopside, epidote and garnet are relatively abundant and wollastonite and its alteration products are relatively scarce. This indicates that the simple chemical readjustment (chiefly $CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2 \uparrow$) of the lower grades, in zone 5 gave way to metasomatism with the



TEXT-FIG. 3.—A triangular diagram showing the fields of the metamorphic zones 1 to 6 in the sediments, plotted from modal analyses of rocks of the Hornfels and Feldspathic Groups. The metamorphic zones form well-defined fields which show the trend towards an increased proportion of feldspars and dark minerals.

Q 100% Quartz + groundmass
P 100% Feldspar
F 100% Ferromagnesian minerals and iron ore minerals.

incoming of basic material (MgO and FeO are clearly indicated) and water. Unfortunately zone 6, which would be expected to show startling differences from the other zones due to the incoming of the alkalis, is not exposed, being obscured by drift. It is interesting to note that wollastonite is the characteristic metamorphic mineral of the lower grades of metamorphism, while diopside together with epidote and garnet mark the higher grades. According to Bowen (1940) diopside should appear in calc-silicate rocks at a lower temperature than wollastonite. In the Glas Bheinn Bheag Calcareous Quartzites, however,

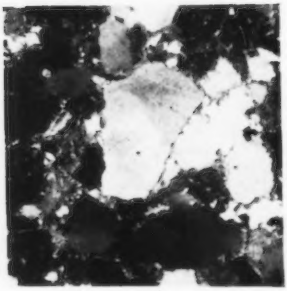
their order of appearance cannot be ascertained. The fact that wollastonite is here more abundant in the lower grades where diopside may be absent, while diopside is in larger quantity in the higher grades where wollastonite may be wanting, is considered to be due to the metasomatic introduction of basic material into the rock: the presence or absence of these minerals does not in this case indicate the metamorphic temperature.

As no chemical analyses of the sedimentary rocks of Glas Bheinn Bheag have been made, a more accurate assessment of the chemical changes undergone by these sediments is not possible. The relationship of the metamorphosed sediments to the microgranite shows that the microgranite is genetically associated with the metamorphism, and thus it is concluded that concomitant with the emplacement of the microgranite, hot aqueous fluids bearing K_2O, Na_2O, MgO, FeO and Fe_2O_3 permeated the sediments. The order of the processes involved was as follows:—

1. Rise in temperature causing recrystallization of the rock:
   (i) detrital quartz → mosaic quartz.
   (ii) detrital feldspar → new feldspar.
   (iii) groundmass → feldspar and dark minerals.
   (iv) calcite and quartz → wollastonite.
2. Further rise in temperature and introduction of K_2O, Na_2O, MgO, FeO, Fe_2O_3 and OH, resulting in increased amounts of feldspars and dark minerals and less quartz and wollastonite.

The contact of the Dunan granophyre with Jurassic sediments has already been the subject of papers by Day (1931) and Black (1955). The former author regarded the junction to be a normal intrusive one, but Black discovered that the granophyre and the sediments were separated by a fault (the Dunan fault), and that the cataclastic rocks of the fault zone had been altered, probably by gases containing Fe, Mg, Ti, and OH.

The sediments of Glas Bheinn Bheag increase in metamorphic grade towards the Dunan fault (see Text-fig. 2), and stratum contouring of the sediments suggests that prior to the development of the fault on its present scale the contact of the sediments with an acidic igneous rock mass was not far beyond the line now occupied by the Dunan fault. The metamorphic zones cut out by the fault are the highest ones which are rich in K_2O, Na_2O, MgO, FeO, Fe_2O_3 and OH. The cataclastic rocks of the fault zone are, as shown by Black (1955, p. 221, Table I), considerably richer in K_2O and Na_2O than the adjacent sediments, and richer in MgO, FeO, Fe_2O_3 and OH than either the sediments or the granophyre. It seems likely that the sediments of the



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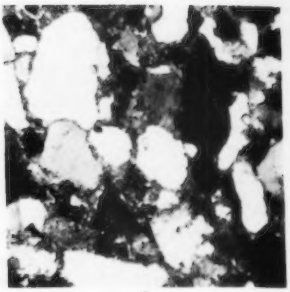

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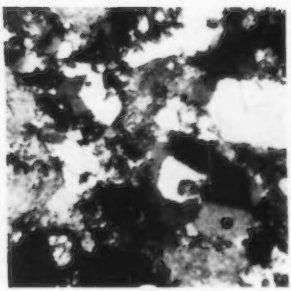

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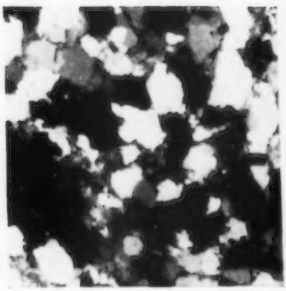

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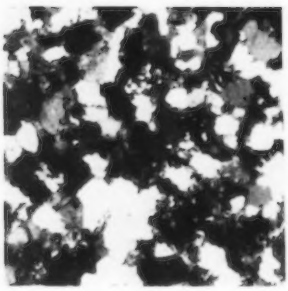

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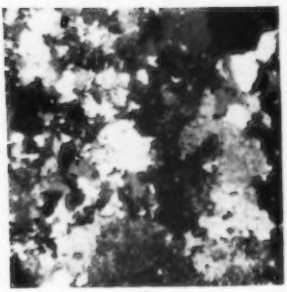

6

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facing p. 473

highest metamorphic zones, especially zone 6 which is totally cut out at Dunan, are represented in the fault breccia, and one wonders how much of the above oxides may have been introduced, as Black suggested subsequent to the faulting, and how much was already present in the rocks at the time when the breccia was formed.

Acknowledgments.—The writer wishes to express deep appreciation of the constructive criticism of this paper by Professor Arthur Holmes, Professor Frederick H. Stewart and Dr. George P. Black, under whose supervision this work was carried out as part of a Ph. D. Thesis.

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EXPLANATION OF PLATE XVI

Plate XVI comprises photomicrographs of slices of rocks of the Feldspathic Group of the Jurassic sediments, illustrating typical textural features of the metamorphic zones.

Fig. 1. Zone 1; Fig. 2. Zone 2; Fig. 3. Zone 3; Fig. 4. Zone 4; Fig. 5. Zone 5; Fig. 6. Zone 6.

Corundum in Biotite-Sillimanite Gneiss from near Polgahawela, Ceylon

By P. G. Cooray
and
P. S. Kumarapeli

Abstract

Idiomorphic, pale blue corundum crystals (S.G. = 4·02, n_o = 1·770 ± 0·002) up to one inch long occur as porphyroblasts in a fine-grained biotite-sillimanite gneiss cut by pegmatite veins at Gangoda, 5½ miles south of Polgahawela. The field relations and petrography of the corundum-bearing rocks are described briefly. The corundum is thought to have crystallized by metamorphic differentiation in alumina-rich silica-poor bands in a semipelitic gneiss.

Introduction *

Among the precious stones for which Ceylon is famous, blue sapphire, a variety of corundum, is the best known and most sought after. Gem quality corundums are all obtained from the alluvial gem gravels which occur as lenses and bands in the river and stream valleys of the Ratnapura District, but within the last 55 years only five instances of the occurrence of corundum crystals *in situ* have been recorded. Of these only one has been of gem quality corundum.

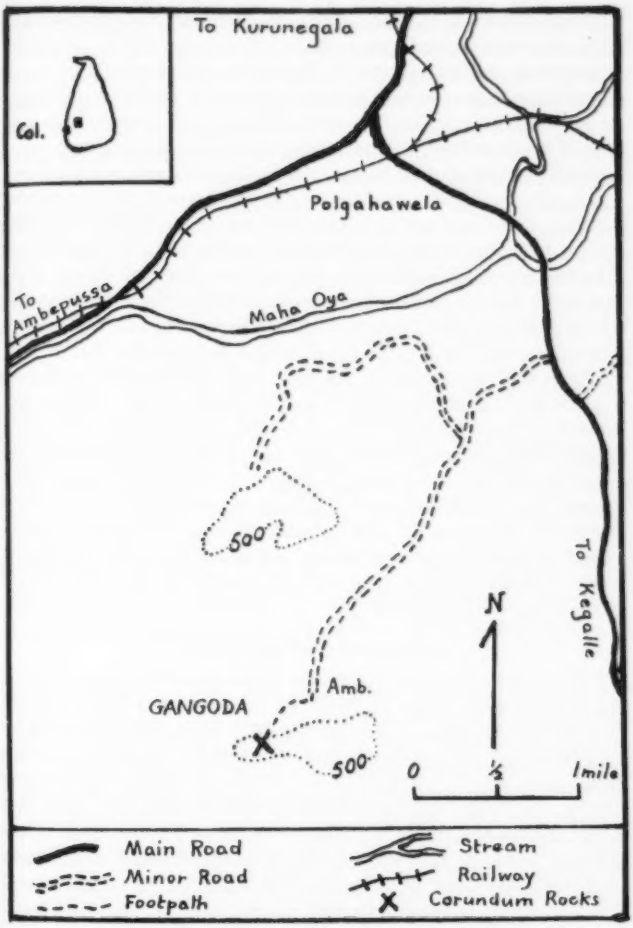
Any such occurrence is therefore of considerable interest not only economically but also because corundum-bearing rocks are of special petrological interest.

The authors are indebted to Mr. B. K. Basnayake for bringing to their notice the present occurrence which occurs on his private property and for arranging a visit by one of them to the locality.

Previous Records of Corundum

The first record of the occurrence of corundum *in situ* was by A. K. Coomaraswamy in 1903 when he described hexagonal prismatic blue sapphires occurring in a felspathic granulite at Tannahena, ¾ mile north-east of the Talatuoya bridge near Kandy. In spite of excavations to a depth of 30 ft. no examples of the fresh rock suitable for detailed microscopic examinations were obtained by him. The corundum-bearing rock occurred as narrow bands (3½ to 7 in. wide) amongst normal varieties of granulite, i.e. acid leptynites. A band of crystalline limestone occurred close by but according to Coomaraswamy there was nothing to suggest any connection between it and the presence of corundum. He considered the corundum to have resulted from " local

* Paper read at the 13th Annual Session, Ceylon Association for the Advancement of Science, December 1957, and published by permission of the Government Mineralogist, Ceylon.



TEXT-FIG. 1.—Map showing location of corundum-bearing rocks.

variation in the constitution of the consolidating magma ", rather than from contamination of magmatic material by aluminous material.

In 1904 the same author described fallen blocks of a corundum-sillimanite rock on Haldummulla Estate near Haputale, in which the corundum formed violet-coloured hexagonal crystals, often with a tabular habit. The actual occurrence of this rock was recently located

and described by A. J. Wells (1956). Wells found that the corundum-sillimanite rock passed eastwards into a friable, white, quartz-sillimanite-rutile rock and westwards, first into a corundum-sillimanite-cordierite-almandine-pyroxene granulite and finally into a quartz-plagioclase-pyroxene granulite. Wells considered the corundum to have formed in a localized bauxite deposit during regional metamorphism, the high concentration of alumina being due to lateritic weathering.

J. S. Coates, in 1935, described corundum in the form of hexagonal pyramids up to one inch long associated with feldspar and biotite in a narrow zone bordering a sill-like biotite-pegmatite in decomposed granulite from Aparekka near Matara, and also as barrel-shaped crystals of gem quality in decomposed felspar apparently connected with a pegmatite vein from the edge of Horton Plains. However, no detailed descriptions of these occurrences were given by him.

The most recent record of the occurrence of corundum *in situ* has been by Wells (*op. cit.*) from near Non Pareil Estate, Ohiya. The corundum here is in the form of conspicuous blue and blue-green hexagonal prismatic crystals of gem quality and occurs between the micaceous margin of a band of crystalline limestone and a syenite. It is associated with pale mauve spinels, a little calcite and phlogopite in a granular aggregate of well twinned oligoclase-andesine, partially altered to scapolite and containing aggregates of fibrous sillimanite. Wells concludes that the corundum has formed by the desilication of syenite magma by limestone.

Location and Accessibility

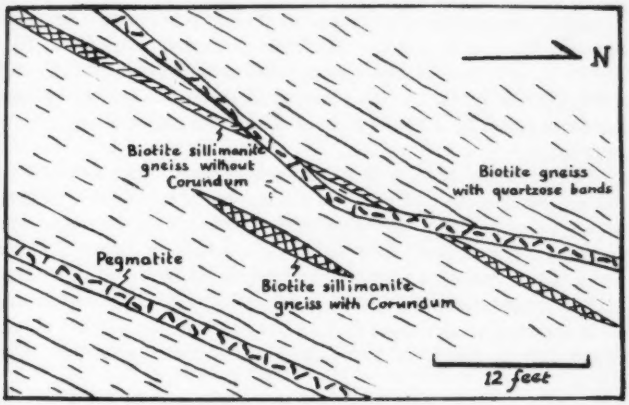
The village of Gangoda is situated about 3¾ miles directly SSW of Polgahawela and nearly 2¾ miles SE of the 11th milepost on the Ambepussa-Kurunegala road (Text-fig. 1). It is reached by a minor road branching off westwards just before the 2nd milepost on the Polgahawela-Kegalle road. The minor road is motorable for about 3 miles, until the *ambalam* (travellers' rest) is reached. From this point a foot-path is followed through a paddy field and a rubber estate belonging to Mr. B. K. Basnayake until the western side of a prominent ridge is reached where the corundum-bearing rocks are found (marked X in Text-fig. 1). The rocks are well exposed at this point.

Corundum-Bearing Rocks and their Associates at Gangoda

(*a*) *Field Relations.*—The country rocks of the Gangoda area are interbanded charnockites and fine-grained biotite gneisses, the latter probably belonging to the pre-Cambrian metasedimentary Khondalite Group of Ceylon. At Gangoda itself the biotite gneisses form a band 100 yards wide running in a NNE-SSW direction and are light-coloured

and equigranular in texture. They contain narrow, highly quartzose bands with an average width of 2 inches, disposed parallel to the strike and standing out as miniature ridges on the weathered surface of the rock. Pegmatite veins run almost parallel to the strike but are sometimes transgressive (Text-fig. 2).

The corundum-bearing rock occurs as lenticular bands within the biotite gneiss and is completely conformable with the latter. Two such



TEXT-FIG. 2.—Geological sketch map showing field relations of corundum-bearing rocks.

bands were noted in the area investigated. The bands are not very wide, being about 11 in. across at their widest, and one of them was followed along the strike for about 50 ft. An interesting feature of the occurrence is that on either side of where a pegmatite crosses the longer of the bands, corundum is absent (Text-fig. 2).

(*b*) *Petrography*.—The biotite gneiss (K.3169A*) is a fine-grained rock composed of quartz, plagioclase and biotite, with zircon, apatite, rutile and green spinel as accessories. The texture is equigranular with a certain amount of foliation imparted to it by the preferred orientation of the biotite flakes. Quartz (avg. grain size 0·8 mm.) occurs mostly as irregularly shaped individuals and forms, with plagioclase, the groundmass ; it is clear except for a few dust-like trains of inclusions. Some of the quartz grains show strain polarization. Sodic plagioclase occurs as irregularly shaped grains with an average grain size of 0·7 mm. It is well twinned, both fine and broad lamellae being present, and signs

* Figures refer to specimens and slides in the Collection of the Geological Survey of Ceylon, Department of Mineralogy, Colombo 2.

of strain such as distorted lamellae, irregularity of twinning and undulose extinction are common.

The corundum-bearing rock (K.3169B,D) is macroscopically similar to the country rock except for the presence of scattered blue corundum crystals, which stand out on the weathered surface, and of sillimanite in prismatic, needle-like crystals. It is, however, markedly different in thin section, quartz being totally absent and plagioclase being subordinate to alkali feldspar. The latter is in equigranular individuals and is highly microperthitic with abundant hair perthite, though some coarse types may be present ; undulose extinction is common. Sillimanite is well oriented and concentrated along certain narrow, well-defined bands parallel to the foliation of the rock. It may be completely enclosed by a single grain of feldspar or may cut across grain boundaries.

The corundum occurs as isolated porphyroblasts which stand out on the weathered surface of the rock and appear in thin section as large colourless grains with well-developed rhombohedral partings. The corundum is invariably surrounded by a sheath of potash feldspar which, when compared with the groundmass, shows: (1) an increase in the average grain size (0·7 mm. in groundmass, 3·0 mm. in sheath); (2) a decrease in the amount of biotite which in the feldspar sheath occurs only as minute flakes; and (3) the complete absence of sillimanite.

The orthoclase, besides increasing in grain size, also becomes more coarsely perthitic, some of the plagioclase inclusions showing vague twinning.

It is interesting to note that the corundum-bearing gneiss from Gangoda appears to be almost identical with that from Tannehena (Coomaraswamy, 1903), except for the absence of garnet and the presence of sillimanite. The feldspathic sheath in the present instance is specially noteworthy because it resembles the " court " of feldspar free from biotite which surrounds the corundum in the Tannehena occurrence. Still more striking is the description of similar sheaths, in xenoliths, of microperthite, feldspar, corundum, sillimanite, rutile and green spinel which occur in hypersthene-bearing biotite gneisses from the Salem District, S. India and described by Holland (1900, 236). In the words of Holland, " Each large corundum crystal is surrounded by a distinct crystallization ' court ' of granular felspar, slightly coarser in grain than the rest of the matrix, and practically free of the accessory minerals. The felspars of the xenoliths are perfectly granulitic in structure, the granules being crossed by streams of sillimanite needles, which as usual, disregard the crystal boundaries of their host and strike across the boundary lines from one granule to another." Armours of some other mineral between corundum and quartz have

also been noted in corundum-bearing siliceous schists which form part of the country rock into which the Dawross peridotite of Connemara is intruded (Rothstein, 1957).

Modal analyses of the biotite-gneiss and the corundum-bearing biotite-sillimanite-gneiss were made on a Swift point counter and the results are given in Table I. Also included for comparison is the result of a mineral analysis of the decomposed corundiferous rock from Tannahena from Coomaraswamy's paper (1903).

TABLE I

	1	2	3
Quartz	39·3	nil	—
Plagioclase	53·8	9·00	23·5
Orthoclase	2·7	74·6	64·2
Biotite	3·5	9·8	4·7
Sillimanite	nil	2·5	—
Remainder *	0·7	4·1	7·6†
Specific gravity	2·73	2·70	

* Ores, apatite, zircon, (?) spinel, rutile.
† Heavy minerals mainly corundum.

1. Biotite-gneiss (K.3169A), Gangoda.
2. Biotite-sillimanite-gneiss (K.3169D), Gangoda.
3. Corundiferous rock, Tannahena (Coomaraswamy, 1903).

The pegmatites, some of which cut obliquely across the country rock and the corundum-bearing bands, are composed of quartz, potash feldspar, plagioclase and biotite. The quartz has sutured margins and trains of dust-like inclusions, and exhibits marked strain polarization. The potash feldspar is microperthitic orthoclase in which a little patchy microcline twinning has developed. Some plagioclase occurs on the edge of the thin section examined. Prominent myrmekite is present in embayments protruding into the potash feldspar. Biotite is pleochroic from yellow to dark green and irregularly-shaped zircon grains occur either within or on the edge of the biotite. The contact between the pegmatite and the country rock is perfectly gradational and is marked by the presence of prominent myrmekite.

(c) *Physical and Optical Properties of Corundum.*—Corundum occurs as hexagonal crystals of prismatic habit. The majority of the crystals are about ½ in. long but some are up to 1 in. in length. The commonest forms developed are hexagonal prism of the second order $\{11\bar{2}0\}$, the positive rhombohedron $\{10\bar{1}1\}$, and a hexagonal pyramid of the second order $\{22\bar{4}3\}$. Partings parallel to (0001) and $(10\bar{1}1)$ are present, the former well-developed but interrupted and the latter prominent. The rhombohedral parting is due to twin lamination and imparts three sets of striations which intersect to form triangular patterns on the basal pinacoid. These parting planes are planes of weak cohesion and consequently the crystals are brittle. The prism

and rhombohedral faces have a vitreous lustre but the lustre on the basal pinacoid tends to be pearly.

Specific gravity was measured on hand-picked fragments by suspension in Clerici solution diluted with water and the refractive index was determined, for sodium light, at room temperature by the immersion method using a Leitz Jelly Refractometer. The results obtained were:—

$$\text{S.G.} = 4{\cdot}02,\ n_o = 1{\cdot}770 \pm 0{\cdot}002.$$

Partings and the internal fractures present render the crystals valueless as gems.

Paragenesis

Two features are noteworthy in the occurrence of corundum-bearing rocks at Gangoda. Firstly, they occur as narrow bands among rocks of probable metamorphic origin and, secondly, the pegmatite in the vicinity has no connection with the formation of corundum in these bands, since this mineral is absent on either side of where the pegmatite crosses one of the corundum-bearing bands; corundum also occurs in a band not cut by the pegmatite.

The occurrence is similar to those at Tannahena (Coomaraswamy, 1903) and at Haldummulla (Wells, 1956) where bands of corundum-bearing granulite occur interbanded with acid granulites and pyroxene granulites. Coomaraswamy himself recognized that the corundum-bearing rocks were due entirely to a local variation in composition in the rocks at Tannahena; although he thought the latter were magmatic, the association of limestone with them suggests that they are really metasediments belonging to the Khondalite Group.

Not enough is known about the surrounding rocks at Gangoda to define the metamorphic conditions under which they crystallized, but the association of perthitic orthoclase, sillimanite, spinel and corundum in the corundum-bearing bands suggests that they formed under conditions of high grade regional metamorphism. According to Fyfe, Turner and Verhoogen (1958) microcline is the characteristic alkali feldspar of the almandine-amphibolite facies, and perthitic orthoclase that of the granulite facies. Further, corundum is present with sapphirine in rare silica-poor assemblages in the pyroxene granulite facies. There are in fact very few descriptions of corundum-bearing assemblages in metamorphic rocks similar to those from Gangoda from outside Ceylon, and the closest parallels appear to be those from within the island, viz. Tannahena and Haldumulla.

It seems likely that the corundum-bearing bands at Gangoda are the metamorphosed equivalents of silica-poor sediments and that the variation of rock types represents compositional changes in a dominantly sedimentary succession. The main change would have been from a semipelitic sediment now represented by a biotite gneiss

to a pelitic sediment (with a preponderance of alumina as sericite and kaolin over chloritic material) now represented by the corundum bearing bands. The disposition of the minerals in the corundum-bearing biotite-sillimanite gneiss suggests that the reaction:—

muscovite + quartz → sillimanite and potash feldspar + water

took place in the course of progressive regional metamorphism of the area. The formation of sillimanite from the alumina liberated in the process depends on the availability of free silica, and in certain parts of these bands insufficiency of free silica led to an excess of alumina which crystallized as corundum.

The form in which the corundum crystals at Gangoda occur, viz. as scattered porphyroblasts separated from the groundmass of the rock by a feldspathic sheath, suggests its growth at scattered loci by a process of metamorphic differentiation within the corundum-bearing bands. Such differentiation, due to migration or diffusion of alumina under the influence of local gradients in chemical potential, is a process similar to the growth of porphyroblasts of garnet, albite and cordierite in other metamorphic schists. Further, the excess of alumina could lead to the growth of corundum crystals only in an environment such as that afforded amongst the " newly born " orthoclase crystals.

The absence of corundum from near the pegmatite may be due to a purely local variation in the amount of alumina or to the migration of alumina to the pegmatite from the corundum-bearing band. The non-dilatory nature of the pegmatite and the presence of abundant myrmekite at the contact indicates that it is a replacement body formed during the general regional metamorphism.

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The Distribution of some Elements across the Contacts of Four Xenoliths

By M. G. Farrand

Abstract

Two basic xenoliths were taken from the Shap adamellite and two from the Glen Fyne porphyritic granodiorite. Each specimen was divided into the three parts ; margin and core of the xenolith and the surrounding host rock. Porphyritic alkali feldspar and sphene were separated from each part and the rocks and minerals were analysed for trace elements and for Na and K. Four specimens of the assumed parent rocks of the xenoliths were also analysed. The results indicate that the two host rocks are similar in trace element content, that equilibrium between minerals in host rock and xenoliths extends to their trace element content and that late stage magmatic fractions may have played a part in the alteration of the xenoliths.

Introduction

The investigation was limited to xenoliths of more basic composition than their host rocks since these remain discrete during alteration. Two specimens from each of two localities were analysed. The Shap Granite quarry provided fresh specimens of the fine-grained dark inclusions in the adamellite and the outcrops of porphyritic granodiorite in the bed of the River Fyne below Newton Hill are almost as fresh and contain many xenoliths very similar in appearance to those of Shap. In both localities the xenoliths are rounded with sharp contacts and contain porphyroblasts of alkali feldspar in a groundmass sufficiently coarse grained to permit the effective separation of minerals.

For purposes of qualitative comparison between alteration in the xenoliths and that in the contact rocks of the intrusions two specimens of the assumed parent rocks of the xenoliths were analysed from each locality. From Shap Fell two specimens of Borrowdale Volcanics were collected, one a biotite andesite, from Sleddale Pike one foot from the contact and the other, a hornblende andesite, from Wasdale Pike, a quarter of a mile from the contact. From Glen Fyne a specimen of the altered gabbro on Newton Hill and one of the diorite between the gabbro and the granodiorite were analysed.

Petrology

The petrology of the Shap intrusion has been described by earlier authors, notably Harker (1891) and Grantham (1928), and that of the Glen Fyne complex notably by Nockolds (1940). In the present study it need only be noted that both host rocks consist of an essentially similar mineralogy. Hornblende was absent from the analysed specimens of the Shap adamellite, though present elsewhere in the intrusion, and the alkali feldspar of Shap is an orthoclase while that

TABLE 1.—SPECTROGRAPHIC ANALYSES OF XENOLITHS, ETC., FROM THE SHAP ADAMELLITE AND THE GLEN FYNE GRANODIORITE

	S	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.
		%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Na	—	2·5	3·0	2·9	3·8	2·5	3·9	2·8	3·0	3·0	3·5	4·5	4·6	4·1	4·4	3·7	2·2
K	—	2·4	5·7	8·5	6·1	6·7	6·6	7·7	4·6	3·3	3·5	3·9	3·9	3·9	4·1	4·0	7·5
Ga	3	29	27	23	24	21	30	23	33	28	32	30	29	28	29	34	15
Cr	5	63	9	100	78	34	180	190	45	450	110	51	34	44	12	19	40
Li	1	36	47	360	280	110	400	470	130	35	24	44	45	31	39	44	16
Ni	5	47	9	57	54	17	79	78	18	270	53	43	34	23	19	30	13
Co	1	23	6	10	8	5	14	15	5	20	12	17	9	7	14	14	6
Cu	1	230	15	49	27	7	22	11	13	5	2	170	170	7	250	180	6
V	10	220	100	94	92	45	112	120	37	140	120	150	97	44	140	130	46
Zr	100	260	250	400	440	140	470	410	190	270	230	570	220	140	420	400	120
Sr	100	700	640	330	580	590	340	260	360	410	940	1,100	960	720	1,100	1,000	1,100
Pb	20	2	23	21	27	28	17	10	26	2	10	12	18	14	16	15	24
Ba	100	1,400	1,200	570	450	820	740	720	510	1,000	1,000	520	530	1,500	580	530	4,000
Rb	10	160	240	540	500	310	550	780	300	180	95	170	160	95	140	150	150
Cs	1	22	8	28	30	16	25	37	17	4	2	10	5	3	4	5	3

S = Sensitivity. All values in parts per million except for Na and K (wt. %) Ag (S = 2) and Mo (S = 20) below limits of sensitivity in all cases.

Table 1 (legend)

1. Borrowdale andesite, 1 ft. from contact, Sleddale Pike, Shap Fell.
2. Borrowdale andesite, ¼ mi. from contact, Wasdale Pike, Shap Fell.
3. Core of xenolith Q. 1 in Shap adamellite.
4. Margin of xenolith Q. 1 in Shap adamellite.
5. Adamellite surrounding xenolith Q. 1.
6. Core of xenolith Q. 16 in Shap adamellite.
7. Margin of xenolith Q. 16 in Shap adamellite.
8. Adamellite surrounding xenolith Q. 16.
9. Contaminated gabbro, Newton Hill, Glen Fyne.
10. Marginal diorite, Newton Hill, Glen Fyne.
11. Core of xenolith GF. 2 in Glen Fyne granodiorite.
12. Margin of xenolith GF. 2 in Glen Fyne granodiorite.
13. Granodiorite surrounding xenolith GF. 2.
14. Core of xenolith GF. 3 in Glen Fyne granodiorite.
15. Margin of xenolith GF. 3 in Glen Fyne granodiorite
16. Granodiorite surrounding xenolith GF. 3.

of Glen Fyne is a microcline but otherwise the same minerals occur in the two rocks and display the same habit and intergranular textures.

The differences in mineralogy between the host rock and the xenoliths of one intrusion lie in modal proportion, habit, and grain size. No difference was discovered in the optical properties of individual minerals in the two environments. Chemical similarity in the case of orthoclase from Shap is shown by analyses published by Spencer (1938).

Preparation of Specimens

The specimens were divided into the three parts ; host rock, margin of the xenolith and core of the xenolith. Dimensions of the xenoliths used are as follows :—

Shap	Q. 1.	$15\frac{1}{2} \times 5 \times 4$ in.
	Q. 16.	$7\frac{1}{2} \times 6 \times 5\frac{1}{2}$ in.
Glen Fyne	GF. 2.	$7\frac{1}{2} \times 6\frac{1}{2} \times 5$ in
	GF. 3.	$10\frac{1}{2} \times 9 \times 8\frac{1}{2}$ in.

A standardized procedure was adopted for the separation of each mineral. The porphyritic alkali feldspar was broken out of the rock with a hammer and pincers and was passed through 80 mesh nylon cloth. Purification was effected with a Franz electromagnetic separator,

Table 2.—Spectrographic Analyses of Porphyritic Alkali-Feldspar

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
	%	%	%	%	%	%	%	%	%	%	%
Na	—	1·6	1·7	1·8	1·6	1·3	1·3	1·0	1·5	1·3	1·4
K	—	12·8	10·8	11·6	9·4	14·5	11·6	10·5	12·5	11·3	11·6
Ga	47	28	30	36	31	24	28	24	25	29	31
Li	28	15	11	15	11	23	22	12	22	18	15
Cu	4	3	3	7	1	19	16	8	17	10	4
Sr	500	570	4,400	2,900	940	1,000	1,000	910	1,200	1,200	1,100
Pb	160	70	100	110	90	44	57	47	55	57	60
Ag	3	5	*	*	*	*	*	*	*	*	*
Ba	1,400	3,000	2,300	1,900	3,100	4,700	6,300	7,600	11,300	13,300	6,500
Rb	270	630	500	500	490	330	230	210	250	240	240
Cs	7	9	5	6	9	1	*	*	3	*	*

All values in p.p.m. except Na and K (wt. %). * indicates below limit of sensitivity (see Table 1).

Table 2 (legend)

1. From xenolith Q. 1 in Shap adamellite.
2. From surrounding adamellite.
3. From core of xenolith Q. 16 in Shap adamellite.
4. From margin of xenolith Q. 16 in Shap adamellite.
5. From surrounding adamellite.
6. From core of xenolith GF. 2 in Glen Fyne granodiorite.
7. From margin of xenolith GF. 2 in Glen Fyne granodiorite.
8. From surrounding granodiorite.
9. From core of xenolith GF. 3 in Glen Fyne granodiorite.
10. From margin of xenolith GF. 3 in Glen Fyne granodiorite.
11. From surrounding granodiorite.

followed by repeated centrifuging in bromoform-benzene mixtures of specific gravity just greater and just less than that of the samples. Very little hand-picking was found to be necessary.

The sequence evolved for the purification of sphene concentrates

began with a rough bromoform separation dealing with 10 grammes at a time in a large funnel. The Franz separator then removed most of the ferromagnesian minerals. This was followed by centrifuging in, successively, bromoform, methylene iodide, and Clerici's solution and by a second electromagnetic separation. Hand-picking was necessary as a final stage.

Analysis of Samples

Sodium and potassium were determined with a flame photometer and the trace elements were analysed by anode excitation in a 240 volt d.c. arc using a large Littrow spectrograph with glass and quartz prisms. The analyses were limited to rocks, alkali feldspars and sphenes and the elements were determined in three groups by quantitative methods as outlined by Ahrens (1954).

The alkali elements, Li, Rb, and Cs, were determined together, using glass optics and a wave-length range of 4,600–9,600 A. Exposure

Table 3.—Spectrographic Analyses of Sphene

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
Ga .	5	5	4	5	5	4	*	3	4	4	3	3
Cr .	250	220	260	240	240	250	220	200	220	200	200	240
Ni .	10	15	14	21	24	8	7	7	7	5	7	9
Mo .	52	67	38	60	81	35	100	95	95	81	95	67
Co .	11	15	15	18	21	24	18	22	23	13	18	17
Cu .	28	34	115	18	17	32	27	23	16	30	22	16
V .	750	730	530	720	850	570	670	850	730	640	770	660
Zr .	1,400	1,500	1,000	12,000	13,000	1,100	7,900	7,800	7,400	6,500	7,500	7,400
Pb .	87	120	100	140	110	80	35†	76	70	220	140	180

All values in p.p.m. Ag, Ba below their limits of sensitivity (see Table 1) in all cases. Sr not detectable owing to excessive background from CN 4606 A.
† Determined by Dr. S. R. Taylor.

Table 3 (legend)

1. From core of xenolith Q. 1 in Shap adamellite.
2. From margin of xenolith Q. 1. in Shap adamellite.
3. From surrounding adamellite.
4. From core of xenolith Q. 16. in Shap adamellite.
5. From margin of xenolith Q. 16. in Shap adamellite.
6. From surrounding adamellite.
7. From core of xenolith GF. 2. in Glen Fyne granodiorite.
8. From margin of xenolith GF. 2. in Glen Fyne granodiorite.
9. From surrounding granodiorite.
10. From core of xenolith GF. 3. in Glen Fyne granodiorite.
11. From margin of xenolith GF. 3. in Glen Fyne granodiorite.
12. From surrounding granodiorite.

was limited to the period of alkali metal distillation and Na was used as a variable internal standard. Sphene was not analysed. For the volatile elements, Ga, Cu, Pb, and Ag, exposure was similarly cut short, but quartz optics and a wave-length range of 2,750–4,680 A were used without internal standardization. To lengthen the period of alkali-metal distillation for the sphene samples a 1 : 1 mixture of the mineral and K_2SO_4 was arced. The same wave-length range and optics were used for the involatile elements, Cr, Ni, Mo, Co, V, Zr, Sr, and Ba, but the samples were arced to completion. A 1 : 4 mixture

of sample and graphite powder was used for the rocks and sphenes and a 1 : 9 mixture for the feldspars. The latter dilution was necessary in order to reduce the emission of Sr and Ba to a readable intensity. The analyses were carried out in triplicate and the results are given in Tables 1, 2, and 3.

Discussion

In comment on the limited data presented no conclusions are justified but some suggestions are made.

Values obtained for most of the elements in the host rocks are close to published average values for granites. However, the agreement between concentrations of the elements in the Shap adamellite and the Glen Fyne granodiorite appears close enough to support a suggestion that the two intrusions may have a related parent magma and a similar cooling history. The differences in the concentrations of Sr, Ba, and Rb in the two intrusions are those expected if Stage II Shap adamellite should represent a later stage of differentiation than the Glen Fyne granodiorite. Mineralogical differences are also compatible with such an explanation. The high Li figures for the Shap rocks are comparable with those recorded by Exley (1955) for a hydrothermally altered facies of the St. Austell granite. Hydrothermal action is thought to have produced the Dark Shap variety of the adamellite and is perhaps also responsible for the high Li content of apparently otherwise unaffected rock.

Petrological evidence suggests that alteration of the xenoliths has gone far enough to produce equilibrium between the composition of minerals in the xenoliths and that of the same minerals in the surrounding host rocks. The analyses show that variation in the trace element content of alkali feldspar and sphene from the host rocks and xenoliths is erratic but is generally small enough to suggest that equilibrium is virtually complete in the trace element content of these minerals. The rock analyses show that this does not lead to equality in concentration of a given element in the two contrasting rock types, but that the concentration varies in sympathy with the mode of the minerals in which the element occurs.

The analyses of the parent rocks and of their contact-altered equivalents suggest that movement of trace elements during the alteration of the xenoliths has in most cases been roughly similar to that occurring during alteration of the country rock.

Taylor, Emeleus, and Exley (1956) suggested that anomalous K : Rb ratios in some magmatic rocks indicated that the magmas had reached a stage of differentiation more typical of a pegmatitic phase than of normal acid igneous rocks. The K : Rb ratios of host rocks and xenoliths have been plotted on the diagram used by Taylor, Emeleus,

and Exley, and although none of the rocks may be said conclusively to lie in a field of enrichment in Rb, all the xenoliths are enriched relative to their host rocks. The evidence encourages a suggestion that the alteration of the xenoliths took place late in the cooling history of the intrusions, at a stage when partial magmas of pegmatitic type had become concentrated. K : Cs ratios follow a very similar pattern to that of the K : Rb ratios. Both these trace elements are probably contained mainly in the biotite.

The essential similarity between alkali feldspar from the host rocks and that from the xenoliths suggests that the mineral crystallized at the same time and under similar physical conditions in the two environments. There is no evidence to suggest that a subsequent recrystallization imposed a similar texture and composition on feldspars in host rock and xenolith. It is thus possible that the alkali feldspar crystallized late in the cooling history of the intrusions when the major part, at least, of the magmatic rock had already solidified and conditions did not differ greatly in host rock and xenolith.

Acknowledgments

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Kilauea Magma 1959–60

By C. E. Tilley

Abstract

Variants of the 1959–60 eruptions of Kilauea are compared chemically with the preceding flank eruptions of 1955.

Eaton and Richter (1960) have now presented a preliminary account of the eruption of November–December, 1959, at Kilauea Iki, a pit crater on the east edge of the Kilauea Caldera, Hawaii, and of the subsequent flank eruption at Kapoho (13th January–6th February, 1960) (Richter and Eaton, 1960). The first phase of activity began on 14th November and lasted for a week and according to Dr. K. J. Murata (personal communication), Director of the Volcano Observatory at Kilauea, the first products were picritic in character. Dr. Murata has very kindly forwarded a lava of this first phase collected on 23rd November, representing material that oozed out of cracks in the surface crust of the pond of lava at a point 75 feet north of the main vent. Further specimens including a tachylyte in the form of spatter thrown out between 18th and 21st November, have been gratefully received from Professor G. A. Macdonald of the University of Hawaii. Both of the basalts now referred to have been subject to analysis by Mr. J. H. Scoon, the results being set down in Table 1.

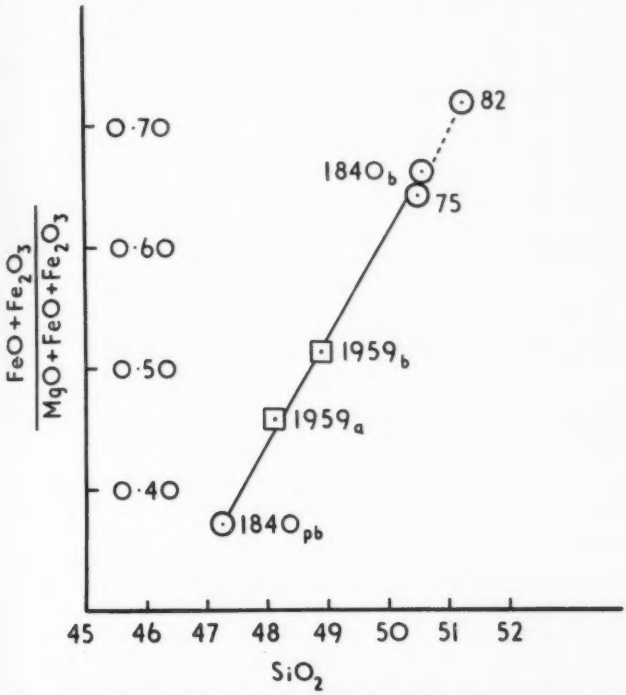
Table I.

	1	2		Norm 1 (*a*)	2 (*a*)
SiO_2	48·91	48·13			
Al_2O_3	12·42	11·62	Or	2·78	2·78
Fe_2O_3	1·34	1·27	Ab	18·34	17·29
FeO	10·23	10·40	An	22·80	21·13
MnO	0·15	0·18	Di	22·24	20·43
MgO	10·96	13·78	Hy	16·08	12·83
CaO	10·44	9·64	Ol	10·25	18·70
Na_2O	2·20	2·04	Il	5·02	4·56
K_2O	0·54	0·50	Mt	1·86	1·86
H_2O+	0·02	0·01	Ap	0·67	0·51
H_2O-	nil	nil	Rest	0·02	0·01
TiO_2	2·64	2·38			
P_2O_5	0·25	0·23		100.06	100·10
	100·10	100·18			

Olivine Basalts, Kilauea Iki, Hawaii; Eruptions of November, 1959.
1. First phase of eruption (14th–21st November) (1959*b* of Fig. 1).
2. Spatter from lava thrown out between 18th–21st November (1959*a* of Fig. 1).

The first example is very largely crystalline, showing conspicuous phenocrysts of olivine in a base of plagioclase laths, granular clinopyroxene, iron ores, and some residual glass. It compares closely in composition with a variant of the 1921 Caldera eruption with SiO_2

49·16, MgO 10·41, analysis of which is reported in Tilley, 1960, Table 1, No. 1. The second example is a dark tachylyte which in thin section shows conspicuous phenocrysts of olivine with enclosures of magnetite. The glass of this tachylyte has a refractive index of 1·607

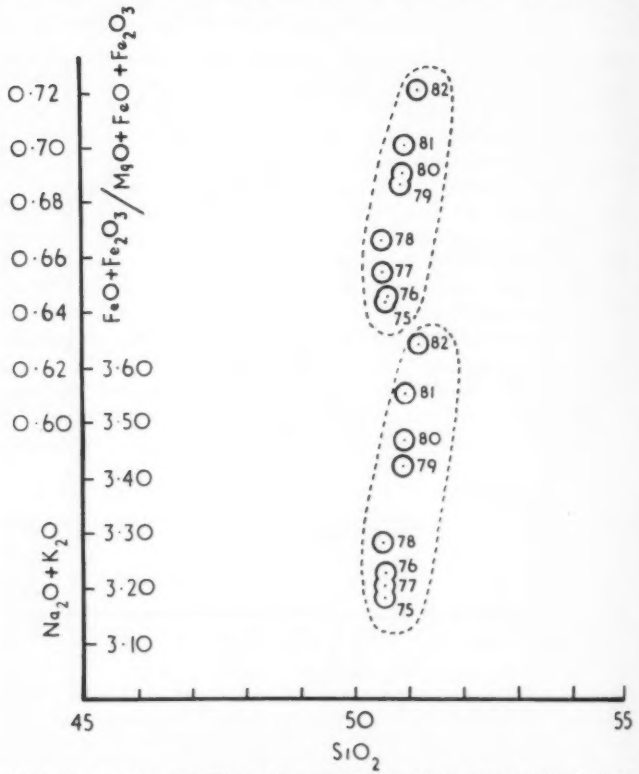


TEXT-FIG. 1.—Plot of analyses of the two lavas of 1959 (iron enrichment/silica) along the Kilauea line of the 1840 picrite basalt-basalt eruptions. Also plotted are the extremes 75 and 82 of the suite of the 1955 eruptions in East Puna (Tilley, 1960, Table 4, p. 53).

which may be compared with the figure of 1·600 for the Pele's Hair of the 1921 eruption (SiO_2 50·04, MgO 6·93, Tilley, 1960, Table 1, No. 4) suggesting that the 1959 glass is somewhat more basic. The high figure of 13·78 MgO in the analysis is, of course, significantly contributed to by the olivine phenocrysts and gives the lava a picritic character.

Both basalts in terms of iron enrichment/silica relationship are characteristically Kilauean products. Their plotted positions in this

type of diagram are shown in Text-fig. 1 in relation to the trend of the 1840 pair of lavas (cf. Tilley, 1960, Text-fig. 1, p. 48). In the figure the trend of the 1955 Kilauean eruptions discussed in the paper just referred to, is also shown in the join 75–82, and in Text-fig. 2 the



TEXT-FIG. 2.—Plot of analyses (iron enrichment/silica, alkalis/silica) of the series of eight lavas of the 1955 eruption in East Puna.

relations of the suite of eight analyses of this eruption are presented in greater detail (iron enrichment/silica, alkalis/silica). The fractional crystallization process which is responsible for the 1955 variation must involve separation principally of plagioclase and pyroxene, in distinction to olivine separation for the 1840 lava pair, for it is to be noted that in the 1955 suite, increasing silica is associated with decreasing lime. The less siliceous of the 1955 suite carry conspicuous

olivine, but in the most siliceous (82), olivine is only sparingly present. The type of extract likely to be responsible for the variation through the series is indicated in Table 2. The principal members of the

TABLE 2.

	75/76	82	*X*	*Y*		*Norms* *X*	*Y*
SiO_2 .	50·60	51·24	47·68	48·78			
Al_2O_3 .	13.77	13.60	14.54	14.25	Or .	0·56	1·67
Fe_2O_3 .	2·31	1·87	4·31	3·56	Ab .	9·43	13·62
FeO .	9·63	11·19	2·52	5·19	An .	34·19	30·58
MnO .	0·17	0·18	0·13	0·14	Di .	34·19	29·18
MgO .	6·59	5·12	13·28	10·77	Hy .	6·20	14·35
CaO .	10·27	9·03	15·92	13·80	Ol .	7·98	2·05
Na_2O .	2·50	2·81	1·09	1·62	Il .	1·22	3·04
K_2O .	0·70	0·83	0·11	0·35	Mt .	6·26	5·34
$H_2O \pm$.	0·04	0·03	—	—	Ap .	0·17	0·34
TiO_2 .	3·17	3·74	0·57	1·55			
P_2O_5 .	0·35	0·41	0·08	0·18		100·20	100·17
Rest .	—	0·09	—	—			
	100·10	100·14	100·23	100·19			

75/76. Average of analysed lavas (75 and 76) of 1955 Puna eruption, Kilauea, flows of 28th March, S.W. of Opihikao, East Puna (Tilley, 1960).

82. Lava of 28th February, 1955, at Pohoiki Road, S. of Honuaula Cone, East Puna.

X. Composition of extract (18 per cent) removed from 75/76 to yield 82.

Y. Composition of extract (26 per cent) removed from 75/76 to yield 82.

crystallate as seen from the norm calculation show only subordinate amounts of olivine. These compositions (X and Y of Table 2) should be contrasted with the crystal extract calculated for the 1840 picrite basalt-basalt pair (Muir and Tilley, 1957, Table 1, p. 242).

The first lavas extruded in the flank eruption in 1960 are reported to be very similar chemically and mineralogically to the lavas erupted in 1955, but near the end of January, the nature of the lava gradually changed, olivine phenocrysts became abundant and during the last week of strong lava output in February, the composition was nearly identical with that of the earlier eruption at Kilauea Iki (Richter and Eaton, 1960, pp. 996–997).

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Co-existing Pyroxenes in Metamorphic Rocks

By M. J. O'Hara

Abstract

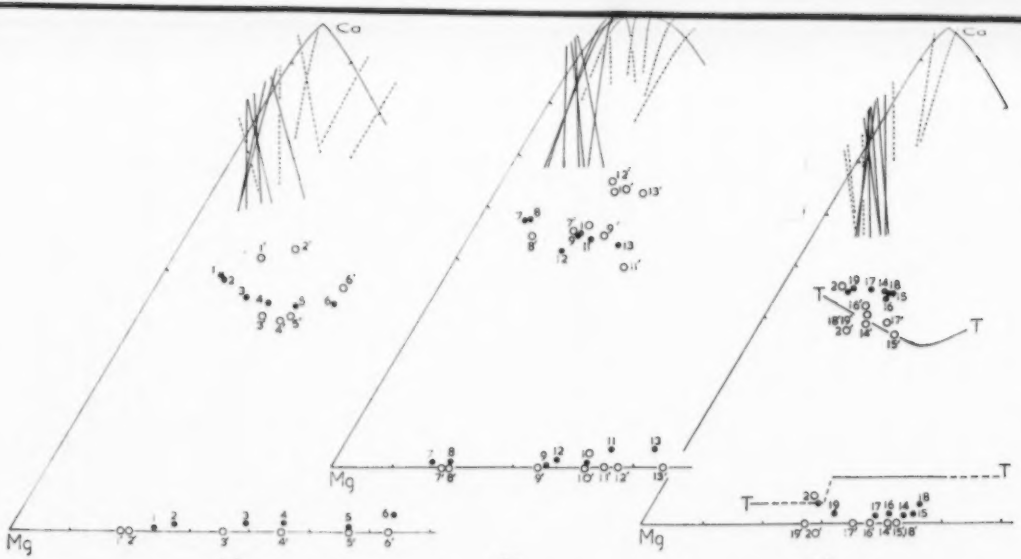
Chemical and optical data for eighteen granulite facies pyroxene pairs are compared. Compositions and tie-line trends derived from optical data are shown to be unreliable and it is recommended that no attempt be made to subdivide the granulite facies on the basis of optically derived tie-lines.

Wilson (1960) has suggested that it may be possible to subdivide the granulite facies on the basis of the optically derived tie-line trends for co-existing clino- and orthopyroxenes. Earlier (Muir and Tilley, 1958) it had been noted that the tie-line trends for analyzed pyroxenes from five metamorphic rocks (two of granulite facies, three of pyroxene hornfels facies) did not depart significantly from those observed in plutonic igneous rocks (Hess, 1941). It was also noted that the compositions of these pyroxenes obtained from optical data and the tie-lines so derived were unreliable.

Compositions and tie-lines for analysed pyroxene pairs from granulite facies rocks of three provinces are presented in Text-figs. 1 (*a*) and 1 (*b*). Data for the pyroxenes of metagabbros from the Pennsylvania-Delaware province are shown in Text-fig. 1 (*c*). These rocks may also belong to the granulite facies. The compositions of the same pyroxenes derived from optical data via the charts of Hess (1949, 1952) are also shown, together with parts of the optically derived tie-lines. Where the optical data permitted more than one estimate of composition for one pyroxene the averaged result is shown. In general the different optical estimates for each pyroxene showed close agreement with each other except in the case of one clinopyroxene from the Madras charnockite series (commented on by Wilson, 1960, p. 10).

Anomalies in the optically derived compositions of clinopyroxenes are conspicuous, both 2V and refractive index differing from the values expected. The error introduced by estimating orthopyroxene composition from the refractive indices is less conspicuous.

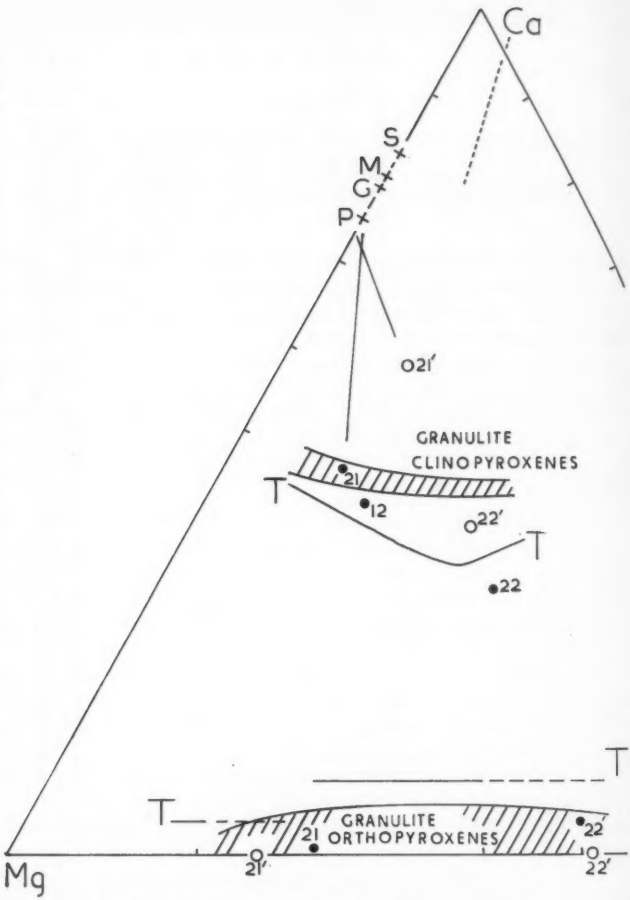
Data for granulite facies rocks are summarized in Text-fig. 2 where the range of intercepts of tie-lines derived from chemical data is indicated and mean values of intercepts for the three provinces shown. This diagram conforms to the observation of Muir and Tilley (1958) that the chemically derived tie-line trends of metamorphic rocks do not depart significantly from those of plutonic igneous rocks. The differences in the mean values of the intercepts from the three provinces may have some genetic significance but the data is insufficient to justify such an interpretation. Differences between the three provinces are



TEXT-FIG. 1.—(*a*) Ca-Mg-Fe + Mn atomic proportions plot for pyroxenes from the Madras charnockite series, rocks 1–6 of Table 1. Points and solid tie-lines are based on chemical analyses. Open circles 1′–6′ are compositions of the same pyroxenes based on optical data. Parts of the tie-lines (broken) are shown for the optical results.

(*b*) Plot and ornament as in Text-fig. 1 (*a*). The points 7–11 and 12–13 represent data for granulite facies rocks from Scourie, Scotland, and Lappland respectively.

(*c*) Plot and ornament as in Text-fig. 1 (*a*). The points 14–20 represent data for metagabbros from Pennsylvania and Delaware which may belong to the granulite facies (compare pyroxene compositions with the range of compositions found for co-existing pyroxenes in the Skaergaard intrusion, curves T-T (Brown, 1957).



TEXT-FIG. 2.—Plot as in Text-fig. 1. The range of intercepts of twenty chemically derived pyroxene tie-lines from granulite facies rocks (including Pennsylvania-Delaware province) is indicated. P = mean intercept for Pennsylvania-Delaware province, M = mean intercept for Madras province, S = mean intercept for Scourie province, and G = mean for all granulite facies assemblages. A field of clinopyroxene compositions from granulite facies rocks containing two pyroxenes is shown. Data for an eclogite facies rock, 21, and a partly amphibolized dolerite, 22, are plotted, the ornament being as in Text-fig. 1. The curves T-T for pyroxenes from the Skaergaard intrusion are reproduced to illustrate the composition differences between igneous and granulite facies pyroxene pairs.

too small, and the spread of results too great to allow the chemically derived tie-line to be used even as a criterion of igneous or metamorphic origin. Any attempt to divide the granulite facies on the basis of differences in optically derived tie-line trends unsubstantiated by chemical analyses would clearly have little significance. Some other pyroxene data from a rock of eclogite facies and another showing alteration under amphibolite facies conditions are included in Text-fig. 2.

Five points raised by Wilson (1960) deserve comment. First, the specimens from the Scourie province were collected within a few miles of each other. Wide geographical distribution of the specimens and possible differences in the geothermal history of the specimens cannot be used to explain discrepancies in the optics of these pyroxenes. Secondly (Wilson, 1960, Fig. 1), it is hoped to attach significance to the trend of optically derived tie-lines from " charnockitic granulites " (all containing orthopyroxene with less than 50 per cent $FeSiO_3$) which differ slightly from those from " intrusive charnockitic granites " (all of which contain orthopyroxene with more than 50 per cent $FeSiO_3$). The observed difference in the trend may arise entirely from the difference in bulk composition of the specimens. Both chemically derived and optically derived tie-lines for the data of Text-figs. 1 (*a*) to 1 (*c*) show a tendency to intersect with larger intercepts on the Ca-Mg axis as Fe/Mg of the assemblage increases. Thirdly, Wilson's statement that " Diopside is obviously unstable in the presence of garnet in the granulite facies . . ." applies only to rocks with free silica. The paragenesis augite-hypersthene-garnet-plagioclase is a common silica deficient assemblage in the Scourie district (O'Hara, 1960a). Fourthly, the " eclogites " of Sittampundi (Wilson, 1960, p. 10; Subramaniam, 1956, p. 355) are granulite facies rocks which should not be referred to the eclogite facies (O'Hara, 1960b). Lastly, the contamination of analysed pyroxene samples by the other pyroxene in the rock (Wilson, 1960, p. 13) cannot possibly affect the trend of the tie-line so derived.

Data for the pyroxenes of a meta-peridotite from Ireland and a peridotite from Webster-Adie are plotted in Text-fig. 3, and conform to the other

TEXT-FIG. 3.—Plot as in Text-fig. 1. Chemical data only are shown for non-feldspathic peridotites from Ireland, 23, Webster-Adie, 24, and for eight peridotite nodules in basalt, 25–32.

pyroxene parageneses. The plot of eight pairs of pyroxene analyses from peridotite nodules in basalts from widely distributed localities are also shown, and are of great interest in that the tie-lines mostly intersect on the Ca-Fe axis, and the clinopyroxenes are unique in having a higher Fe/Mg ratio than the associated orthopyroxenes.

TABLE 1

Key to data shown in Text-figs. 1–3.

India.

Madras charnockite series (Howie, 1955).

1. Ultrabasic charnockitic rock (3390).
2. ,, ,, ,, (4645).
3. Intermediate charnockitic rock (2270).
4. Basic charnockitic rock (2941).
5. Basic charnockitic rock (4642A).
6. Intermediate charnockitic rock (115).

Scotland.

Scourie granulite facies gneisses.

7. Peridotite with amphibole and spinel (Muir and Tilley, 1958, T).
8. ,, ,, ,, (O'Hara, 1960a, X 282).*
9. Garnet-augite gneiss with hypersthene and plagioclase (O'Hara, 1960a, X 646).*
10. Plagioclase-two pyroxenes granulite (Muir and Tilley, 1958 S).
11. ,, ,, ,, (O'Hara, 1960a, X 291).*

Lappland (Eskola, 1952).

12. Plagioclase-two pyroxenes granulite, Härkäselkä.
13. Plagioclase-two pyroxenes hornblende granulite, Koddigvärri.

United States of America.

Pennsylvania-Delaware province (Clavan, McNabb, and Watson, 1954; Norton and Clavan, 1959).

14. Megagabbro (35–5N).
15. " Quartz-norite " (35–6N).
16. " Quartz-diorite " (35–8N).
17. " Fine grained massive gabbro " (35–9N).
18. " Hypersthene diorite " (35–13N).
19. " Hornblende eucrite " (35–19N).
20. " Eucrite-norite " (35–32N).

Other rocks.

21. Garnet-hornblende-pyroxenite, Glenelg, Scotland (O'Hara, 1960b, G.8).
22. Amphibolized dolerite, dyke in gneiss at Scourie (O'Hara, 1960a, Z 145).* Both analyzed pyroxenes of this rock contain abundant intergrown pyroxene of the other type. Optical data indicate the compositions shown in Fig. 2 for the host-phase in each case.
23. Meta-peridotite, Dawros, Ireland (Rothstein, 1958, R).
24. Peridotite, Webster-Adie, U.S.A. (Ross, Foster, and Myers, 1954).
25–32. Peridotite nodules from basalts of Mexico, U.S.A., Germany, Austria, Japan, and Hawaiian Islands (Ross, Foster, and Myers, 1954).

* Chemical and optical data for the pyroxenes of these rocks will be published shortly.

Conclusions

Differences in the distribution of Ca, Mg, and Fe between co-existing pyroxenes do exist and are probably due in part to variation in the conditions of formation. Available data for metamorphic pyroxenes amounting to twenty-five paired analyses, confirm the observation that the chemically derived tie-line trends do not depart significantly from those of plutonic igneous rocks. The data demonstrate that the only reliable approach is by chemical analysis and it will be interesting to see analyses of the pyroxenes from Wilson's Central Australian charnockitic rocks.

Acknowldgements

I wish to thank Professor F. H. Stewart and Professor C. E. Tilley for critically reading the manuscript. Studies of the pyroxenes from the rocks of the Scourie district were made while a research student in the Department of Mineralogy and Petrology, Cambridge, during the tenure of a maintenance grant from the Department of Scientific and Industrial Research.

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A note on Current-bedded Moines near Garve, Wester Ross

By N. J. Soper

(PLATE XVII)

Abstract

A locality in the Moine series at which well preserved current-bedding may be viewed in three dimensions is described. An analysis of the foreset dip directions shows that the sediment was deposited by current flowing in a direction slightly east of north. The form of the current-bedding is described and the significance of the observations briefly discussed.

Current-bedding has long been known to be present in the Moine Series of north-western Scotland. It was first recorded in Sutherland by officers of the Geological Survey before the turn of the century. Since then it has been met with sporadically over much of the area of outcrop of the Moines and has proved invaluable in the determination of the direction of younging of the beds in regions of complex structure.

The orientation of the current-bedding has also aroused interest. Wherever the direction of dip of the foreset beds has been recorded it has been found to be in a general northerly direction, indicating derivation of the sediment from the south (Wilson, Watson and Sutton, 1953). It is, however, unusual to find exposures on which the current-bedding may be viewed in three dimensions, as is necessary for an accurate analysis, and the impression that northerly dips predominate over the other foreset directions has been gained from numerous observations of the attitude of foreset beds as seen in two dimensions only. This preliminary note describes a locality at which well preserved current-bedding may be seen in three dimensions.

The locality is a water-filled quarry immediately west of the bridge of the Ullapool road over the Black Water, 1½ miles N.N.E. of Garve, Wester Ross (Grid ref. NH.402640). It is situated in an area in which sedimentary structures are particularly well preserved. A few miles to the west, in the Fannich Forest, current-bedding has been observed at more than fifty localities and has been particularly useful in the determination of structure and succession (Sutton and Watson, 1954). To the north, current-bedding, together with rain pits, mud cracks and ripple marks are preserved in the hornfelses associated with the Carn Chuinneag-Inchbae orthogneisses (Harker, 1956).

The quarry is in a fine grained psammitic schist, light grey when fresh, with bedding planes and cross-bedding lamellae well marked by a darker grey colouration. The rock is composed essentially of quartz, potash feldspar, plagioclase, biotite and muscovite, with the following

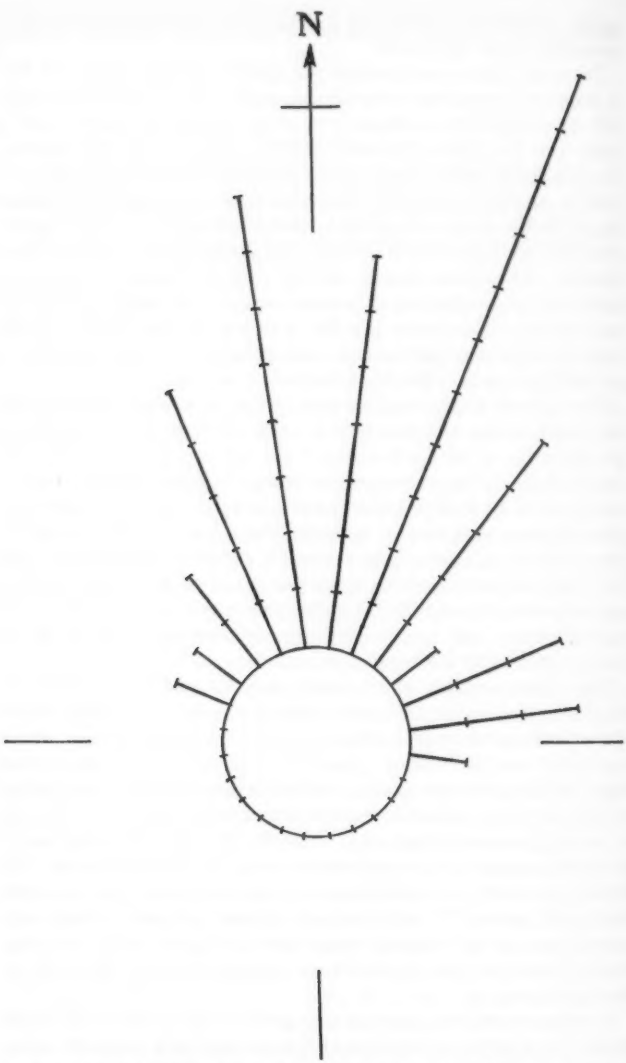
modal composition: quartz 68, K-feldspar 18, plagioclase 6, biotite 4, muscovite 3 (vol. per cent).

The quartz forms a sutured mosaic, grains averaging about 0·4 mm. in diameter, containing trains of numerous minute opaque inclusions and often exhibiting undulose extinction. Potash feldspar occurs in larger anhedral grains frequently showing hazy microcline twinning. The plagioclase builds smaller anhedral grains, clouded with alteration products and rarely twinned; the composition is in the albite-oligoclase range. Biotite forms small flakes, pleochroic in straw and dark brown, often showing alteration to chlorite. Muscovite occurs in larger flakes, together with smaller masses secondary after feldspar. Accessories include zircon, commonly in minute well rounded grains, apatite and rare epidote. The darker lamellae marking bedding planes are not easily recognised in thin section, but appear to be characterized by an increase in mica content, particularly muscovite.

The style of folding is such that the beds are almost horizontal over much of the quarry exposure. Open flexures of low amplitude plunge gently to the north-west and are well exposed in the adjacent river section. In the quarry several groups of sharp overfolds may be seen, each in the form of one or several compound synclines and anticlines of two or three metres amplitude. These folds plunge to the south-west and their axial planes dip to the S.E. or S.S.E. at between 15° and 30°. Two well developed systems of vertical joints are present, striking approximately 10° and 280°, enabling the current-bedded units to be viewed on two joint faces roughly at right angles. Joint faces are frequently studded with small pyrite cubes.

The current-bedding is on a small scale, units averaging 4·6 cm. in thickness; individual foreset lamellae are a few millimetres thick. Topset beds are invariably absent and the current-bedding is of the type which has been termed " planar cross-stratification " (McKee and Weir, 1953), the lower bounding surfaces of the units often being planar erosion surfaces. These features are illustrated in Plate XVII. Groups of several current-bedded units may be separated by units which show pronounced horizontal lamination but no current-bedding; this feature was useful in determining which bedding planes were originally horizontal and which were inclined erosion surfaces. Small scale crenulations of the bedding planes simulate ripple marks but when viewed in section may be seen to be a tectonic feature. The beds are the correct way up.

Readings were taken on projecting corners of the quarry wall, formed by the intersection of the vertical joints, and were confined to the southern part of the quarry where the beds are nearly horizontal between two of the sharp overfolds mentioned above. All the units showing current-bedding on any particular corner were measured, with



TEXT-FIG. 1.—Rose diagram based on 48 foreset dip directions in psammitic schist, Moine Series, 1½ miles N.N.E. of Garve, Wester Ross. Class interval 15°.

the exception of those obviously involved in washout structures. The following data were recorded for each unit as seen on the two joint faces:—

(*a*) Strike of joint face; (*b*) Dip of top of unit; (*c*) Dip of base of unit; (*d*) Maximum dip of foreset lamellae; (*e*) Thickness of unit.

If (*b*) and (*c*) differed by more than a few degrees and neither could be related to a horizontally laminated unit, the current-bedded unit was assumed to be involved in a washout and the data discarded. Dip readings of the true and foreset bedding as viewed on two faces were finally obtained for 48 units. The readings were confined to a vertical range of about 4 metres and the same unit may no doubt have been recorded more than once. With the aid of a sterographic projection the true dip of the unit and of the foreset lamellae within it were calculated; the original (post compaction) direction and amount of dip of the foreset lamellae, assuming the units to have been laid down horizontally and there to have been no subsequent attenuation of the beds, were then found.

As the direction of plunge of the major fold axes in the immediate area are not known, it was necessary to reorientate the current-bedding by simple rotation of the beds into the horizontal position about their strike. This does not correct for rotation in the horizontal sense, but it is thought that the error thus introduced is small (see discussion in Knill, 1959).

The direction of dip of the foreset lamellae is shown in text-fig. 1 which illustrates that the directional field is in the northerly quadrant, dips rather to the east of north being commonest. The sediment at this particular locality and horizon may confidently be said to have been deposited by a northerly flowing current. These results would seem to add weight to the view, based on less detailed observations of current-bedding made over a wide area of outcrop of Moine rocks, that the Series as a whole was derived from the south.

The average dip of the foreset lamellae is 11°. The present form of the current-bedded units bears some resemblance to that of the " local delta foreset beds " described by McKee from the middle portion of the Colorado delta, which were composed of fine sand with a concentration in grain size around 0·2 mm. (McKee, 1939). While it is unreasonable to make a direct comparison because of the possibility of post-compaction attenuation during folding, and other factors, it does seem probable that the sediment in this area was originally a silt or fine sand, deposited on the subaerial portion of an extensive river delta.

The dissimilarity between the types of sediment of the Moine and Torridonian Series, and also between their directions of derivation, as factors against possible correlations between the two series, has been

fully discussed elsewhere (see Wilson, Watson and Sutton, 1953). The Torridonian sediments are coarser and often strongly current-bedded with foreset beds inclined to the south-east or east as compared with the finer sediments and north or north-north-easterly dipping current-bedding of the Moines. However, the Epidotic Grits of Skye, the lowest division of the Diabaig Group, have recently been shown to have been deposited by currents flowing to the north-east or east (Sutton and Watson, 1960).

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EXPLANATION OF PLATE XVII

Joint face in psammitic schist, 1½ miles N.N.E. of Garve, Wester Ross, showing current-bedded units, planar erosion surfaces and horizontally laminated units. Length of hammer 60 cm.

CURRENT-BEDDED MOINE PSAMMITE, NEAR GARVE, WESTER ROSS.

CORRESPONDENCE

DEPOSITION OF THE OLD RED SANDSTONE

SIR,—Dr. K. W. Barr (1960, *Geol. Mag.*, xcvii, 263–264) draws attention to sedimentary features of the Old Red Sandstone of Ekmanfjorden, Vestspitsbergen (Dineley, 1960, *Geol. Mag.*, xcvii, 18–32), which are commonly regarded as typical of, if not restricted to, turbidity current deposits. Depositional features very similar to those Barr singles out are being studied by each of us, as well as by Dr. H. W. Ball, in other Old Red Sandstone formations, British and North American.

The upper Lykta Division (Emsian) of Vestspitsbergen and the Ditton Series (Gedinnian-Siegenian) of the Welsh Borders are strikingly similar lithologically. Each consists dominantly of red or sometimes green siltstones and abundantly of sandstones. Vertebrate-bearing intraformational conglomerates, subordinate to the finer beds, are important units of both successions. Their widely scoured bases mark the abrupt juxtaposition of very differently graded rocks, and appear to define local " cyclothems ". These major groupings, commonly tens of feet thick, seem to recur throughout the upper Lykta Division as well as the Ditton Series. They typically show the following vertical sequence: (1) conglomerate with basal disconformity (2) thick sandstone (3) thick siltstone. Inasmuch as grain size diminishes upwards, these " cyclothems " resemble the graded graywacke-shale pairs of geosynclinal " turbidites ". But in detail, unlike the superficially identical " turbidite " grouping, each " cyclothem " consists of well-defined sedimentation units, often separated by sharp bedding planes evincing subaerial exposure, reworking or brief non-deposition. Each major grouping in the Old Red Sandstone clearly accumulated gradually.

Cross-bedded sandstones in the middle sections of several " cyclothems " at Ekmanfjorden have been transformed into thick slumps (Dineley, p, 25, and text-fig. 3). Similarly contorted beds occur elsewhere in the Old Red Sandstone of Spitsbergen and in the Carboniferous red-beds of St. Jonsfjorden. In most instances slumping apparently ceased before the next bed was formed; in a few, as in convolute bedding, the upper parts of the sandstone flowed after deposition of the overlying bed. Thick sandstone slumps are not known in the Ditton Series, although thin convolute-bedded sandstones and siltstones are not uncommon. The larger structures from these formations are exactly analogous to thick, slumped, cross-bedded sandstones in the Trias of Cheshire (Rice, 1939, *Proc. Liver. Geol. Soc.*, xvii, 361–370). Comparable to the smaller structures are convolute-bedded sandstones and siltstones described from the red-bed Moenkopi Formation of Arizona (McKee, 1954, *Geol. Soc. Amer., Mem.* 61, pp. 56, 65, and plate 8 A-D, 10B). Abundant signs of exposure in the Old Red Sandstone, Trias and Moenkopi suggest that slumping took place in shallows, or perhaps even subaerially.

The linear sole marks reported from Ekmanfjorden (Dineley, p, 26, and text-fig. 4) find parallels in the Ditton Series, the Moenkopi (McKee, p. 63, and plate 9 A-C), and the Lower Keuper around Liverpool (Cummins, 1958, *Liver. and Manch. Geol. Jour.*, ii, 37–43). Flute casts dominate the sole marks in the Ditton Series; load casts and groove casts are not common. As in Vestspitsbergen, suncracks commonly exist within the same thin beds as these bottom markings. Likewise, the Lower Keuper and Moenkopi abound in proofs of exposure—notably reptilean footprints (especially *Chirotherium*), suncracks, rainprints and pseudomorphs—as well as in sole marks. The bottom markings from all these formations are clearly very like those described from typical marine " turbidites ", but the environment where they formed was obviously quite different. " Flash floods " or sheet floods, as Barr suggests, sweeping over the Old Red Sandstone floodplains, may well have been important in the deposition of the coarser beds and in the formation of their sole features. But in our opinion there is no certain evidence that such

floods led to the creation of turbidity currents, in the sense of dense flows beneath bodies of relatively still and clear water, shallow or deep. We believe that the Old Red Sandstone " cyclothems " accumulated more slowly and more uniformly, probably in fluviatile and shallow lacustrine regimes where " normal " currents operated. Interestingly enough, the metamorphosed red sandstone-siltstone measures present in the Dartmouth Slates of South-West England, holding many sedimentary features in common with the Ditton Series, have appeared to certain workers to be a deep-water " flysch ". There is now evidence that these beds are of continental, Old Red Sandstone facies (Dineley, in press).

Discovery of the features mentioned above demands no reversal of our beliefs concerning the deposition of the Old Red Sandstone, either of Britain or Spitsbergen. It does remind us, however, that the production of graded bedding, sole marks and deformational structures is not limited to environments where ill-sorted sediments are deposited rapidly by turbidity currents.

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J. R. L. Allen.
Geology Department
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Reading.

28th July, 1960.

WENLOCK STRATA OF SOUTH MAYO

Sir,—In his account of the stratigraphy and structure of the Wenlock strata of South Mayo (*Geol. Mag.*, 1960, xcvii, 265), Professor J. G. C. Anderson describes two phases of folding affecting the Silurian strata of the Croagh Patrick syncline and assumes that the gently plunging folds which roughly parallel the axis of the major structures are the earliest folds in the area.

I have recently completed mapping the ground immediately to the south of the Owenwee river, and have found that a complicated tectonic sequence of events affects the southern limb of the syncline. The intense stretching of boulders in the basal Wenlock conglomerate is parallel to an *a* direction lying on the axial plane of folds which plunge steeply to the west. These steep folds undoubtedly pre-date the first folds described by Professor Anderson, since the schistosity in the basal Wenlock psammites associated with the steep folds is, in places, deformed by a penetrative cleavage, dipping steeply northwards, which is axial to the first folds of Anderson. The steep cleavage which is prominent on the southern limb of the Croagh Patrick syncline can be shown to be a second structure on another line of evidence, since the folds with which it is associated face downwards, although the major structure faces upwards.

I am unable to agree with Professor Anderson's assertion that the major arcuate swings in strike of the southern limb of the syncline can be referred to a single phase of deformation associated with the north-westward plunging second folds. The major arcuate swing of strike around the northern margin of the Corvock granite is related to the intrusion of the granite stock and Stanton (1959) has shown that the swing in strike north-west of Cregganbaun is undoubtedly due to shearing parallel to the north-west to south-east dextral Maam faults.

J. F. Dewey.

Department of Geology
The University,
Manchester.

7th October, 1960.

REFERENCE

Stanton, W. I., 1959. The Lower Palaeozoic Rocks of South-West Murrisk, Ireland. *Proc. geol. Soc. Lond.* No. 1568, 67–73.

SIR,—Minor structures in the basal Wenlock beds of Co. Mayo are extremely variable, particularly when it is studied as a whole; they include, among others, the steep westerly-plunging folds, mentioned by Mr. Dewey, especially in the matrix of the conglomerate. Moreover, the relation of boulder extension to structure is a controversial problem; the stretching of the boulders can also be interpreted as in a " b " direction parallel to the E.–W. folds including, in part of the S. limb, those plunging gently east.

There is a tendency to regard every different direction of minor structure as evidence of the existence of a separate fold-system irrespective of the nature of the formations and the geometry of their mapped boundaries, whereas minor structures, in different directions, even showing a local sequence, may develop within the one system. The complex structures in the highly inhomogeneous Wenlock conglomerate may well fall into this category; discussion of their possibly wider tectonic significance must await the publication of more detailed evidence than is possible in a letter.

No evidence whatever is afforded for the supposed tectonic effects of the granite. However, consideration of the position of the intrusion in relation to the symmetry of the arc it cuts does not support the view that it is the cause of the arcuate swing. Moreover, detailed mapping, both on its W. margin and on its complex N. margin, shows structures and stratigraphical boundaries striking straight at granite junctions.

Having ascribed the east arm of the Cregganbaun arc to this cause, Mr. Dewey then invokes a second cause for the west arm. (Yet a third must be postulated for the arcing and N.W. folds remote from both granite and fault.) Dr. Stanton, it is true, attributes certain tectonic features in the Ordovician further S. to the Maam faults, but he has not " undoubtedly " shown that the swing in strike N.W. of Cregganbaun is due to these structures.

The Maam fractures are in fact part of a system of N.W. and N.E. tear faults which developed very late and may in fact be due to post-Carboniferous, N.–S. Armorican compression; the arcs, on the other hand, are pre-Carboniferous. These faults are plentiful throughout a wide region and very commonly cut across formations with only very local drag or shear (as do the Maam Faults for part of their course). Where, however, a pre-existing grain approximately in the potential shear-direction exists, a fault will more readily and fully develop, as has happened in the case in question; this does not exclude the possibility of some shearing parallel to the fault-movement.

DEPARTMENT OF GEOLOGY, J. G. C. ANDERSON.
UNIVERSITY COLLEGE, CARDIFF.
18th October, 1960.

DEPTH TO TOP OF POSTULATED WEARDALE GRANITE

SIR,—Gravity surveys have revealed a region of negative Bouguer anomalies over the northernmost Pennines (the Alston Block) which is unrelated to the known geological structure and has been interpreted by Bott and Masson-Smith (1957) as being caused by a buried granite (named the Weardale granite). At that time the top surface of the granite was estimated to be less than 5,000 feet deep. Since the publication of this paper certain advances have been made in the technique of depth estimation from gravity anomalies, and I should like to put on record an improved estimate before it is put to the test in a new borehole which is now being drilled at Rookhope, Co. Durham.

A method of depth estimation recently developed by Smith (1959) relies only on the measured second or third derivatives of the Bouguer anomalies and an assumed value for the density contrast. This method gives considerably " better " estimates than earlier methods (e.g. Bullard and Cooper, 1948; Bott and Smith, 1958) and has the added advantage that knowledge of the background gravity field is not needed. The estimates give *maximum possible depths* for the assumptions stated and refer to the *top surface* of the anomalous body and not to its centre of gravity or base. Therefore the estimate must be treated as a *limit* and *not as the expected depth*.

Smith (1959) has shown that the maximum possible depth to the top of a gravitating body can be estimated from either of the following formulae (slightly adapted):—

$$h \leq 2{\cdot}70\, K|\rho|/|G''|\ \text{max.} \quad . \quad . \quad . \quad . \quad (1)$$

$$h^2 \leq 3{\cdot}13\, K|\rho|/|G'''|\ \text{max.} \quad . \quad . \quad . \quad . \quad (2)$$

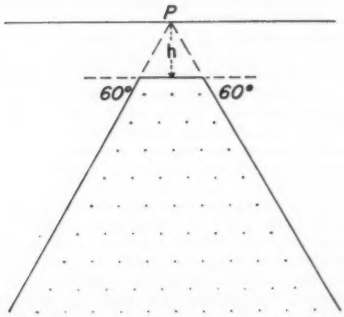
where K is the gravitational constant, ρ is the difference between the maximum and minimum densities of the system, G'' max. is the maximum observed second horizontal derivative of the gravity anomaly, and G''' max. is the maximum observed third horizontal derivative.

If two-dimensional shape can be assumed, formula (1) can be improved by about 4 per cent, as follows:—

$$h \leq 2{\cdot}60\, K|\rho|/|G''|\ \text{max.} \quad . \quad . \quad . \quad . \quad (3)$$

Thus the two-dimensional limiting case is very little different from the three-dimensional limiting case.

A two-dimensional shape exactly satisfying the limiting condition of equation (3) can be constructed as follows. The limiting body (shown in Text-fig. 1) is a symmetrical truncated wedge of uniform density ρ with



TEXT-FIG. 1.—The two-dimensional shape satisfying the limiting condition of equation (3). The stippled portion has a uniform density contrast ρ to the remaining unshaded part and the model extends uniformly to an infinite depth.

a vertical axis. The depth to the truncated top surface, which is horizontal, is h. The edges both dip at 60° (in opposite directions) and the wedge extends to an infinite depth. The maximum value of the second derivative of gravity then occurs at the apex of the wedge (P), and its value is given exactly by equation (3). For any other two-dimensional shape equation (3) gives an overestimate of h.

In this limiting case, each edge contributes equally to the maximum second derivative. If, therefore, one of the edges is sufficiently distant to contribute negligibly to the total second derivative, then we obtain the following limiting formula for a two-dimensional step:—

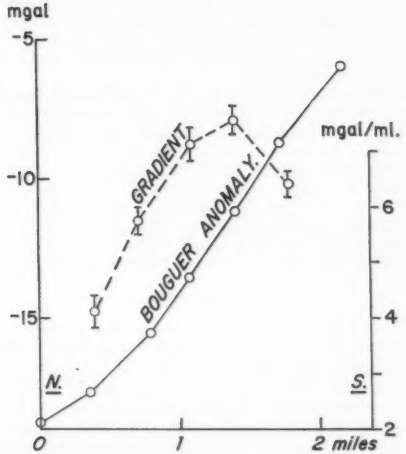
$$h \leq 1{\cdot}30\, K|\rho|/|G''|\ \text{max.} \quad . \quad . \quad . \quad . \quad (4)$$

This formula is of considerable practical use, since the contribution to the second derivative from the more distant edge of many typical geological rock masses is often almost negligible. Such is the case for the postulated Weardale granite.

Detailed gravity traverses have recently been made across the margins of the Weardale anomaly to obtain accurate estimates of the numerical

characteristics needed for depth estimation (Text-fig. 2). The maximum observed second derivative along the Stanhope-Cotherstone road was found to be 4·3 mgals/mile², and if all possible errors are taken into account this value could possibly be reduced to 3·5 mgals/mile². The maximum observed third derivative is 7·5 (± 1·0) mgals/mile³.

In applying Smith's method to the Weardale anomaly, it is assumed that no appreciable errors have been introduced in making the reductions and that the observed characteristics are entirely caused by the body under study.



TEXT-FIG. 2.—The critical part of the gravity traverse along the Stanhope-Cotherstone road, showing Bouguer anomalies reduced for a rock density of 2·60 g./cm.³ and the horizontal gradient of gravity. Each value of the gradient has been measured between alternative stations and for each the range of error which might be expected is shown.

In this latter respect, the Lower Carboniferous rocks exposed at the surface are practically flat-lying and unfaulted, and no thick superficial deposits are known along the line of the observed profile. The vertical variation of the Bouguer anomalies has also been taken into consideration. It is further assumed that the density contrast does not exceed 0·20 g./cm³. If the density contrast is greater (which would be unusual for a granite), the maximum possible depth estimate increases proportionately. It is clear that the northern margin of the anomalous body is sufficiently far away for its effect to be negligible; therefore inequality (4) can justifiably be used.

The results, taking into account the likely and minimum possible observed second derivatives, are as follows:—

for 4·3 mgals/mile², depth to top surface $\leq$ 3,400 feet
for 3·5 mgals/mile², depth to top surface $\leq$ 4,200 feet

This estimate can be checked by using inequality (2) for the observed third derivative of 7·5 mgals/mile³, giving a maximum depth to the top surface of 5,000 feet.

Good estimates of depth can also be obtained by assuming a regular shape

for the body and investigating by methods of trial and error how deep the body may be to give the observed amplitude of anomaly and the observed marginal gradients. While this method is not rigorous, it is likely to be reasonably reliable. Comparison of the observed Weardale profile with two-dimensional computed profiles (using the Durham University electronic computer) suggests that for a density contrast as great as 0·20 g./cm.^{3}, the observed marginal gradients of 7·5 mgals/mile could only occur if the top is about 3,500 feet or less below the surface.

In extending these deductions to Weardale and Rookhope, both of which are north of the critical profile, it is assumed that the top surface of the granite does not become appreciably deeper towards the centre of the mass. Detailed studies on the gravity anomaly suggest that this assumption is broadly correct. Nevertheless local fluctuations could occur without noticeably affecting the anomalies.

It is concluded that the top surface of the postulated Weardale granite is shallower than about 4,000 feet beneath the Stanhope-Cotherstone road, about 4½ miles south of Stanhope. Taking into account the variation in topographic height, the top of the granite should be less than 3,500 feet beneath Weardale and less than 4,000 feet beneath Rookhope provided the stated assumptions are correct. It is not possible from the gravity anomalies to place a minimum limit on the depth although absence of metamorphic effects at the surface suggests it is at least 1,500 or 2,000 feet deep. Thus it is expected that the granite will be reached in the Rookhope borehole between depths of 1,500 and 4,000 feet and most likely between 2,000 and 3,000 feet.

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M. H. P. BOTT.

DEPARTMENT OF GEOLOGY,
SOUTH ROAD,
DURHAM.

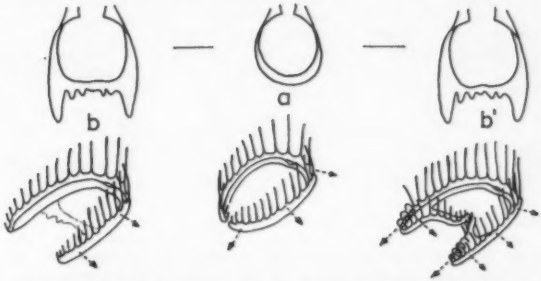
10th October, 1960.

FEEDING MECHANISMS OF SPIRE-BEARING BRACHIOPODS

SIR,—The recent article by Dr. M. J. S. Rudwick on "The feeding mechanisms of spire-bearing fossil brachiopods" is a splendid example of the bold and imaginative use of living material to infer the habits of extinct groups and will certainly be appreciated by all those who decry the rarity of this event in palaeontological practice. But a sincere welcome for the approach is not necessarily an unqualified approbation of the conclusions which, as outlined below, appear to involve some inadequately considered assumptions.

Having demonstrated in 1956 that the internal skeleton of the brachiopod is secreted by outer epithelium in the same way as the secondary shell layer, I can only concur with Rudwick's reiteration that the growth of the lophophore and its calcareous support are independent functions. This, however, does not preclude the intimate connection of one with the other. It is significant, for example, as Mr. A. D. Wright and I have recently said in an article on the origin of the loop (now in press—*Palaeontology*) that even in the

terebratuloids the growth of the loop seems to have exercised sufficient physical constraint to retain the generative tips of the lophophore medianly. In respect of the loop, which is, after all, the fundamental structure of all spire-bearing brachiopods, Rudwick is wrong to speak of the antero-median tip of the *Zygospira* loop *splitting* so that the generative ends of the lophophore " might have diverged, remaining on the tips of the prongs " (p. 371). No split developed: the loop was simply enlarged by resorption along its inner edge and secretion along the outer one, a process which included the accelerated deposition of a pair of antero-lateral extensions. This mode of development is especially well seen in *Protozyga*, newly formed loops of which were rounded or truncated anteriorly (Text-fig. 1a) and the growth of the antero-



TEXT-FIG. 1.—The loop of *Protozyga* with its inferred lophophore below, and interpretations of the subsequent development according to Rudwick (b) and Williams (b'). Broken arrows show the passage of filtered water.

lateral prongs, which were the beginnings of the spiral ribbons, and of fine spines along the anterior margin was patently independent of any " migration " from the median line. Consequently I am still convinced that the lophophore must have surrounded such prongs in such a way as to form a doubled brachial axis like that making up the side arms of *Terebratulina* and that the tips of the lophophore remained adjacent to each other on the jugum (Text-fig. 1b'). I am therefore also of the opinion that " the question of the relation and function of the jugum " is not as open as Rudwick believes it to be (p. 371) and there is some ancillary evidence to support this view. Rudwick (p. 374) has used the disposition of fine spines developed on the spiralia of fossil brachiopods to orientate the lophophore thereon. Such spines are equally common along the anterior edge of the jugum and in some stocks like *Hustedia* (Text-fig. 2a) they also occur in the medio-ventral line of the jugal stem and are disposed in such a way as to fit in very neatly with a postulated pair of incoiled ends to the lophophore situated on the dorso-posterior side of the jugal apparatus (Text-fig. 2b'). Certainly if the spines can be guides to the attitude of the lophophore on the calcareous spires they can be used with equal impunity for its inferred position on the jugum.

In 1956 when attempting to reconstruct the spiriferoid lophophore, I homologized it with the terebratuloid plectolophe and in this light it is less than fair for Rudwick to say " it is difficult to see how the lophophore of spiriferoids as reconstructed by Williams could, for all their wealth of filaments have produced any workable current system " (p. 377). If a system of filter feeding can be demonstrated for terebratuloids then clearly it can also be adapted for the spiriferoids, but before doing so it is pertinent to examine the systems proposed by Rudwick.

One segment of the lophophore which deserves some attention is that containing the mouth. In this ventrally facing median arc the filaments must

always occur on the outer edge so that any current induced by the transverse beating of cilia must move outwards from the centre towards the postero-lateral regions of the mantle cavity. In atrypaceids, with the bases of their spires more or less in the same plane as the median arc, a complete current system could have worked in the manner described by Rudwick and observed by him in *Tegulorhynchia* and by Orton in *Crania*. But in the spiriferoids the entire brachial axis beyond this segment must have rotated through 90° relative to its attitude along the median arc; and if each calcareous ribbon supported, as Rudwick contends, a single brachial axis the only feasible current system is that described by him as "exhalant". The system is, as he admits, unknown in any living inarticulate or articulate

TEXT-FIG. 2.—The jugal apparatus of *Hustedia sp.* (a) from the Word. of Texas and the disposition of the lophophore thereon according to Rudwick (b) and Williams (b'). Unbroken arrows show the passage of unfiltered water, broken ones the passage of filtered water.

brachiopod and although this in itself is not important it may reflect a fundamental disadvantage because in such an exhalant current system the mouth region can only receive filtered water for further filtering.

An alternative scheme applicable to the atrypaceids and spiriferoids alike is one involving the existence of a doubled brachial axis on the calcareous ribbons beyond the jugum. It is shown in Text-figs. 1b′ and 2b′. Unfiltered water arrived postero-medianly and passed antero-laterally into a pair of filter tubes fashioned from interlocking filaments which arched over paired brachial lips. According to this interpretation the filter tubes of *Protozyga* were nothing more than slightly arcuate prolongations of the central lophophorous organ but in later stocks they were spirally coiled. The system may be a cumbersome one, but at least it has the advantage of being a modified inhalant one and is moreover not unique because the filter tube, coiled in a planar spire, is characteristic of living terebratuloids. I concede that in view of Rudwick's studies the coextensive spires of spiriferoids like *Diplospirella* more likely gave additional support to a doubled brachial axis on the primary ribbons. This emendation, none the less, has in no way affected my opinion that the generative tips of the lophophore remained in the median plane of all spire-bearing brachiopods where they were almost invariably supported by the jugal apparatus.

DEPARTMENT OF GEOLOGY, ALWYN WILLIAMS.
QUEEN'S UNIVERSITY, BELFAST.
October, 1960.

SIR,—I am grateful to Professor Williams for enlarging on his interpretation and for giving me an opportunity to clarify my own.

In describing the tip of the loop of *Zygospira* as "splitting" into two prongs, I was aware that this would probably have occurred by differential secretion on the outer edge of the loop and simultaneous resorption on the inner edge—

the growth lines which give evidence for this mode of growth can be clearly seen on the loop of any Recent species. Williams' figures of the loop of *Protozyga* show that the term " splitting " is not appropriate in this genus. But this question of nomenclature does not affect my argument. Once it is agreed that the lophophore is a structure essentially distinct from its supports, the mode of growth of the prongs is irrelevant to the problem of locating the tips of the lophophore. I await with interest Professor Williams' and Mr. Wright's paper on the origin of the loop. Doubtless this will clarify their conception of the " constraint " exercised by the loop on the tips of the lophophore. At present I do not follow this; for in terebratuloids the tips are adjacent to the loop only until the zugolophous stage, and they grow independently throughout the plectolophous stage. I have still to be convinced that the tips ever lay close together on the future jugum; or, if they did, that they could not have migrated on to the prongs as the prongs developed. Such a development of a ring-shaped into a horseshoe-shaped lophophore occurs in *Tegulorhynchia*, and I can still see no reason for drawing a fundamental distinction at this point between rhynchonelloids and spiriferoids.

The crux of my interpretation of current directions depends only on the basically possible orientations of the filaments. The evidence of the fine spines on the spiralia is adduced merely to suggest a more precise reconstruction of the attitude of the filaments. Since writing this paper I have been able, through the courtesy of Dr. G. A. Cooper, to examine some of the specimens of *Hustedia* from Texas, to which Williams refers; and I agree that the spines on the jugum are indeed similar to those on the spiralia. But it does not follow necessarily that the brachial axis extended on to the jugum. Strictly speaking, the spines on the loops of Recent species merely show that surfaces with spines are those not immediately adjacent to other tissues (i.e. the lophophore invariably occurs on the opposite surface). This may be as far as the homology should be taken, Then the spines on the jugum of *Hustedia* may only indicate the presence of *some* organ adjacent to the other side. This would involve modifying my use of the spines as definitive indicators of the presence of the brachial axis; but I am prepared to concede this point, since the main evidence for my interpretations lies elsewhere.

It is not true that on my interpretation of *Spirifer* the filaments near the mouth would have received filtered water, and that an " exhalant " spirolophe would thereby be inherently inefficient. In living species with "inhalant " spirolophes (e.g. *Tegulorhynchia*) these filaments touch some ventral part of the mantle surface, isolating a small exhalant space (leading laterally into the main exhalant spaces) between them and the body wall. Without changing the basic orientation, it is perfectly possible that in *Spirifer* the tips of the same filaments touched some *dorsal* part of the mantle surface, isolating a small *inhalant* space (leading laterally into the main inhalant spaces) between them and the body wall. Thus there is no reason to deny the inherent possibility that *Spirifer* could have had a current system with inhalant and exhalant chambers completely isolated—that is, a system just as efficient as that of *Tegulorhynchia* or *Atrypa*. Regrettably this point, though simple topologically, is difficult to demonstrate clearly without three-dimensional models.

In the light of the criteria of an efficient filter-feeding system (p. 376) I still cannot see how the filaments of *Spirifer*, on Williams' interpretation, could have operated with any efficiency. I made this remark originally with his interpretation of *Diplospirella* chiefly in mind; but even with his retraction of that interpretation the criticism still applies, and I cannot agree that it is unfair. His Text-fig. 2b′ fails to show how the stream of inhalant water (from a median inhalant aperture ?) could have been kept separate from the exhalant water emerging from the nearby spiral " filter tubes "; and thus it ignores the basic prerequisite of functional efficiency. Moreover the whorls of spiriferoid spiralia are placed so close together, and are often so numerous, that Williams' interpretation would demand very long and very narrow " filter tubes "; and on the scale involved these would be very inefficient for

hydrodynamical reasons. (The median spiral of a plectolophe is not a true parallel here, for it is a relatively short and rapidly tapering tube—a shape perfectly adapted to its function.) Finally, his interpretation leaves unexplained the characteristic form of spiralia—the closely-spaced whorls surrounding a wide central space—and their characteristic " moulding " to the shell; and it also leaves as an anomaly the close similarity (in these features) between spiriferoids and atrypoids.

As in most other branches of geology, here too the validity of our interpretations must be judged by the range of unexplained phenomena which they render intelligible. In the present state of knowledge of brachiopod morphology, I prefer to leave open the question of the jugum, since the only apparent alternative is to deprive a much wider variety of structures of any meaningful significance.

SEDGWICK MUSEUM, M. J. S. RUDWICK.
CAMBRIDGE.
3rd November, 1960.

ON *GRYPHAEA*

SIR,—In a recent paper in this magazine (1959a) I sought to demonstrate that the evidence does not support Trueman's classic hypothesis on the gradual evolution of *Gryphaea* from *Liostrea* in the basal zones of the Lias. That part of my work based upon a statistical study of *Gryphaea*, which has a critical bearing on the hypothesis, has been questioned by Dr. K. A. Joysey (1959) on two grounds, involving technique and results respectively.

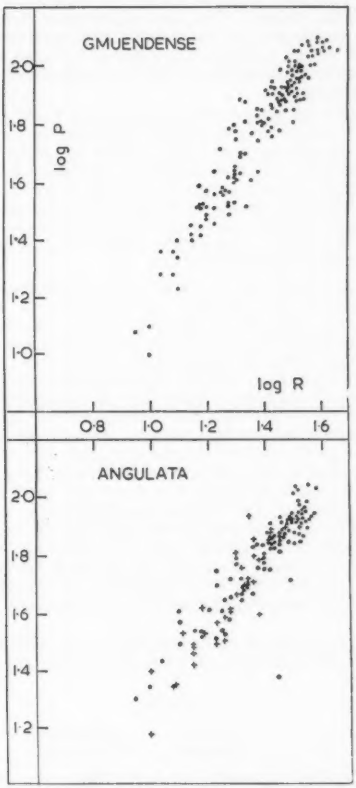
My choice of measurement of the periphery to assess the amount of coiling of the left valve is criticized because it is based upon the erroneous assumption that the left valve conforms to a perfect logarithmic spiral. No such assumption is necessary for the matter in question and I persist in my contention that length of the periphery provides an effective measure of coiling accurate enough to test Trueman's hypothesis. I shall try to demonstrate this. In fig. 1 of his 1922 paper Trueman gave drawings of four specimens from different horizons to illustrate his *Liostrea-Gryphaea* lineage, which one may reasonably presume he regarded as more or less modal, since otherwise the figure loses its point. I have made determinations of the ratio of the periphery (P) to length of right valve (R) of the Glamorgan gryphaeas from the *angulata* Subzone (fig. 1b) and a much higher horizon, queried *gmuendense* Subzone (fig. 1d). (The fact that the specimen of fig. 1b is named as *G. dumortieri* does not affect the issue, since the whole figure purports to illustrate a gradual transition and is misleading in giving no hint that highly incurved gryphaeas occur commonly in the *angulata* Subzone (see below).) I have also determined the mean P: R ratio for my own collections from Glamorgan. The results are given below:

	P: R
Trueman's fig. 1b (R = 3·00 cm.)	1·40
,, fig. 1d (R not determinable since diagram of shell " slightly reduced ".)	3·00
Personal collection:	
angulata Subzone (mean of total)	2·55
,, ,, (R = 2·9 — 3·1 cm.) . . .	2·67
gmuendense Subzone (mean)	2·67

The ratio for the specimen of fig. 1b is markedly at variance with my data; in fact highly incurved forms such as that illustrated in fig. 1d are the dominant element in all my *angulata* Subzone material from England and Wales, as anyone who cares to examine my collections may confirm.

Admittedly this simple method of comparison leaves something to be desired, but it is the best I can do in the absence of an original collection to refer to. It serves adequately, however, to illustrate the point I wish to make, namely that Trueman claimed striking changes in the adult organism which should be clearly revealed even using the periphery only as an approximate

measure of coiling. In my experience in dealing with large assemblages of *Gryphaea* I find this measurement, though admittedly not ideal, the most practicable one. At least it seems more refined than assessment of coiling



TEXT-FIG. 1.—Scatter diagram to show the relationship between the logarithms of the periphery and length of right valve, measured in mm., in *Gryphea* samples from the *angulata* and *gmuendense* Sub-zones of Glamorgan, etc. The material from Dorset is indicated by crosses.

in terms of three or four ¼ whorl units. Granted, it suffers from the deficiency that variation in the earliest stages of coiling in highly incurved forms may be missed, but this is not critical in the circumstances. There is a danger that too much may be read into what Trueman had in mind. He was not particularly concerned, as I see it, with subtle variations in the first few mm. of growth; there is indeed no reference in his paper to the practical difficulties

involved in assessing variation in the earliest stages of highly incurved forms. No problem arises, furthermore, in comparing his drawings 1b and 1d.

Joysey also makes the point that Swinnerton's (1939) material contained, unlike mine, a high proportion of individuals with area of attachment exceeding 2 mm. This may be partly due to his collection having come from localities I have not visited. The point is, however, not relevant, since I rejected none of the oysters I collected and my results must be considered on their own merits. Given samples from different horizons with small attachment areas, important differences should be recognizable if Trueman were only approximately correct.

As regards my results, both Joysey and Swinnerton (1959) have commented on the fact that I lumped together collections from the country as a whole. Although I have made an answer to this objection in my reply to Swinnerton (1959b) I recognize that my case would be strengthened if I could demonstrate that the facts do not support the evolutionary hypothesis even in Trueman's collecting area in the south-west. I have therefore undertaken a further statistical analysis with some of my original data. The technique is the same as that outlined in my earlier paper, using the shortened methods of calculation described by Imbrie (1956).

Trueman's work is based upon collecting done in Glamorgan and Somerset (precise localities were not specified). All my relevant material from the *gmuendense* Subzone came from the Glamorgan coast between Southerndown and Gwter Fawr. Most of the specimens from the *angulata* Subzone were collected either from the Glamorgan coast between Southerndown and Stout Bay or from a quarry at Corston, in north Somerset. As the sample (90) is rather small in comparison to that from the *gmuendense* Subzone, some forty specimens from Lyme Regis have been included. It seems quite legitimate to add material from Dorset to the rest, since Trueman based his ideas on specimens collected from two different counties and Lyme Regis is hardly greater in distance (some fifty miles) from the collecting localities in Glamorgan than are the Lower Lias localities in Somerset. In all areas the facies at the relevant horizon is an off-shore one of alternating calcilutites and argillaceous beds; differences between Dorset and Somerset are especially hard to detect. Nevertheless, to counter possible objection to this pooling of material, data on the Dorset gryphaeas are shown separately on the graphs (Text-figs. 1 and 2) so that readers may judge for themselves whether or not the specimens fall into the same morphological group as those from Glamorgan and Somerset.

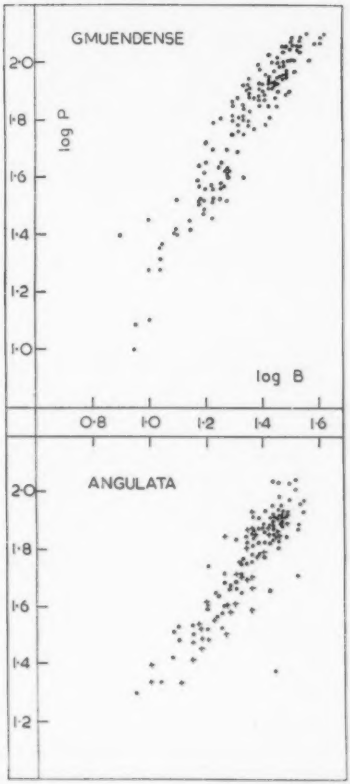
In Text-fig. 1 the logarithms of the periphery (P) and the length of the right valve (R) are plotted as before; the relevant statistics are given in Table 1.

TABLE 1

	angulata Subzone.	*gmuendense* Subzone.
N .	130	151
y .	1·76	1·78
x .	1·37	1·39
S_y .	0·190	0·222
S_x .	0·144	0·154
r .	0·891	0·895
a .	1·32	1·44
b .	− 0·04	− 0·22
a .	0·053	0·053

For Trueman's hypothesis to be confirmed, the slope *a* should be significantly greater for the sample from the *gmuendense* Subzone. In fact there is no significant difference in slope between the samples ($P > 0{\cdot}05$). There is moreover, no significant positional difference. As Joysey thinks that breadth

of the left valve is the most suitable index of size and as Swinnerton has questioned my choice of valve length for this purpose I have also plotted the logarithms of the periphery against logarithms of the breadth of the left valve (B) with the same material (Text-fig. 2 and Table 2). Once more, there



TEXT-FIG. 2.—Scatter diagram as in Text-fig. 1 to show the relationship between the logarithms of the periphery and breadth of the left valve.

is no significant difference in either slope or position ($P > 0{\cdot}05$); the results are indeed very similar to those obtained using R as the size index.

Trueman's hypothesis is a good one in that it makes a claim of pronounced changes which is readily amenable to a simple test, *pace* Dr. Joysey. Differences of detail might be allowed, but any revised version of the hypothesis should follow the broad pattern Trueman outlined. The facts I have gathered in my statistical investigations are at variance with the hypothesis

TABLE 2

	angulata Subzone.	*gmuendense* Subzone.
N .	129	145
y .	1·76	1·78
x .	1·34	1·35
S_y .	0·190	0·222
S_x .	0·125	0·142
r .	0·906	0·902
a .	1·52	1·56
b .	− 0·27	− 0·33
a .	0·054	0·056

that coiling becomes markedly tighter up the Liassic succession but accord with the alternative hypothesis in which *Gryphaea* is regarded as a single, distinct Linnaean species (*G. arcuata*) which underwent no change except that due to a slight increase in size. It seems more reasonable therefore to reject Trueman's hypothesis in favour of the alternative than to postulate a subtle change, manifested only in the young stages, which cannot readily be detected by practicable methods of measurement.

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A. HALLAM.

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EDINBURGH.

SIR,—In my review (1959) I criticized the statistical part of Hallam's investigation (1959a) on two main grounds: namely that the length of the periphery of the left valve of *Gryphaea* is not a suitable measure of coiling, and that the samples consisted of material pooled from several localities. In the foregoing letter Hallam has attempted to answer these criticisms and has presented some additional statistical work in support of his original conclusions. I wish to maintain that my criticisms are justified in relation both to his original and to his present work.

Hallam's graphs show the relationship between the length of the right valve and the length of the periphery of the left valve. These graphs are simply a plot of one size dimension against another, but they are not graphs of the relationship between size and the amount of coiling. This is so because the length of the periphery of the left valve is not a measure of coiling unless the periphery of that shell has the form of a logarithmic spiral, and this is demonstrably not the case. (Maclennan and Trueman, 1942.)

Trueman (1922) stated that: " The arching of the left valve increases until it is coiled through more than one and a half whorls." Trueman's graph is graduated in terms of whorls, and this measure of coiling is directly comparable with Swinnerton's measure (1932) in terms of the " angle of rotation ", which he apparently measured to the nearest 5 degrees. In contrast, Hallam refers to the length of the periphery of the left valve as though it were a measure of coiling, although it is in no way comparable with that used by Trueman. This is illustrated in Text-fig. 1 which shows two profiles that are identical both

TEXT-FIG. 1.—Two profiles which are identical both in the length of the periphery of the left valve and in the length of the right valve, but which differ in the amount of coiling (¾ and 1¼ whorls). The small area of attachment indicates the original orientation of the shell.

in the length of the periphery of the left valve and in the length of the right valve, but which differ in the amount of coiling. If Hallam insists upon using an approximate measure of coiling which does not distinguish between shells differing in the total amount of coiling, then any possible difference between the two samples may easily be obscured, and the fact that he finds " no significant difference " has no meaning.

In the foregoing letter, Hallam's comparison of the P/R ratio of his *angulata* Subzone sample with that of Trueman's Fig. 1b appears to be somewhat misplaced. Fig. 1b is an illustration of *Gryphaea dumortieri*, a species which Hallam (1959a, pages 105–6) has previously dismissed as a mere phenotypic variation of *Liostrea irregularis*, under the name *L. irregularis*, var. *dumortieri*. Hallam has previously pointed out that measurement of the periphery would not be satisfactory as a means of comparing *Liostrea* and *Gryphaea* (1959a, p. 100). Furthermore, he stated that *L. irregularis* is sharply replaced by *G. incurva* just below the top of the *angulata* Zone (pp. 106–7), whereas his own sample was collected from the highest part of the *angulata* Zone (p. 100).

Hallam rightly states that Trueman's hypothesis is based upon a consideration of the adult organism, but he appears to forget that the adult shell represents the whole life history, including those parts laid down during the juvenile stages. It is inescapable that Trueman's assessment of the total coiling of an adult shell included coiling during juvenile stages. If Hallam chooses to discount the importance of the juvenile stages, and uses a method which obscures differences in the amount of coiling of the umbo, then he will inevitably obscure any possible difference between his samples.

Hallam has noted that his samples, unlike Swinnerton's (1939) collections, do not contain many individuals with an area of attachment exceeding 2 mm., and has suggested that this may be partly due to the collections having come from different localities. Contrary to Hallam, I regard this point as being relevant, insofar as it illustrates the importance of phenotyphic variation in this oyster material.

I maintain that in the present case it is bad practice to pool samples from different localities and treat them as though they were drawn from a single population. There is substantial evidence that the relationship between size and coiling is subject to phenotypic variation, and the factors responsible for

phenotypic variation may not be reflected in the sediments. If, as seems likely, phenotypic differences are superimposed upon the supposed evolutionary sequence, then one can hardly hope to elucidate the problem by using coarse sampling methods. Referring to Hallam's present graphs, I agree that readers must judge for themselves whether the dots and crosses have the same trend, line or whether perhaps the crosses tend to lie towards the right of the dots in the lower part of the scatter.

In his additional statistical work Hallam has used the breadth of the left valve as an alternative size dimension, but finds little difference from his previous results. This improvement in the choice of the size dimension is wasted unless he also abandons the length of the periphery of the left valve as a measure of coiling.

I concluded my previous article (1959) on this subject with the statement: " Reviewing the various quantitative methods which have been applied to the study of the *Ostrea-Gryphaea* series has led me to the opinion that most of the statistical evidence is open to criticism and does not provide a sound basis for any conclusion. Until further evidence on the relationship between size and coiling becomes available, the only possible verdict is Not Proven." Despite Hallam's additional statistical work, I still hold this opinion. With reference to the statistical evidence it is impossible to judge whether it is Trueman or Hallam who has reached the right conclusion for the wrong reasons.

Some who have read my *Biological Review* article have expressed regrets that I reached no conclusion. But this is not correct. I concluded that the available evidence does not justify most of the conclusions which have been drawn by previous workers. I used the existing data to make a number of suggestions, and drew attention to some of the difficulties which would inevitably arise in the interpretation of the results of any further investigation. It is true that I reached no solution to the *Gryphaea* problem. This raises the question whether any solution is possible. Oysters are notoriously variable and few would regard them as ideal material on which to base a study of an evolutionary series. In the present case it is demonstrable that the extent of phenotypic variation at the top of the succession is comparable with the supposed evolutionary change throughout the succession. Under these circumstances one must be realistic and accept that the Liassic *Ostrea-Gryphaea* series is intrinsically unsuitable material for this type of investigation. While it might be instructive to try to obtain some more data on the relationship between size and coiling, the results of any further work are likely to be amenable to more than one interpretation.

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K. A. JOYSEY.

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" DELTAIC " CYCLOTHEMS

SIR,—In principle, steady even subsidence *by itself* seems capable of determining the birthplace and subsequent cyclothemic life-history of a " delta ". No more need be put into a general theory. All " deltas " can be considered as possessing innate tendencies to overlengthen and short-circuit

repeatedly. *Leave one alone in a subsiding region and it will produce regression-transgression cyclotheme without further interference.*

The simple theory is deducible from the classic Mississippi researches of Fisk, Russell, and the workers they inspired. Dr. A. J. Wells (*Geol. Mag.*, 1960, xcvii, pp. 389–403) just fails to formulate it, though usefully comparing the importance of various factors known to influence " deltaic " sedimentation.

Dr. D. Moore has shown that certain Yoredale cyclothems are substantially explained " without recourse to more fanciful ideas " (*Journ. Geol.*, 1959, pp. 522–539). Prof. A. Bersier proved the same for the Molasse (*Eclog. Geol. Helv.*, 1959, li, pp. 854–893, esp. fig. 4). Twelve years ago (XVIIIth Int. Geol. Congress) I applied the idea to Wealden cyclothems. New knowledge since has necessitated upgrading certain factors (e.g., eustatic changes of base-level) and my position is now close to Dr. Wells's.

P. ALLEN.

DEPARTMENT OF GEOLOGY,
UNIVERSITY,
READING.

10*th November*, 1960.

REVIEWS

THE EVOLUTION OF NORTH AMERICA. By PHILIP B. KING. pp. 189 with 96 text figs. and one folding map. Princeton, Princeton and Oxford University Presses, 1959. Price 60*s*.

Formulated as a series of lectures, this book is the first coherent and readable account of the geology of North America. The undergraduate audience required the frequent explanations of general principles and concepts in geology which, to a foreign reader not using this as his first approach to geology, seem oddly out of place. The lecturing style has not been concealed and this allows a free and colloquial expression of views, often controversial yet without laborious qualification. There is indeed textual evidence of the stenographic mode of production which from lesser lips is becoming a menace. On the other hand, the elementary nature of the exposition makes for simplicity and the book can be read straight through with rewarding clarification and without the burden of over much detail.

In using North America as a type continent to develop his ideas on crustal evolution, one of the most distinguished American geologists gives us the benefit of a sustained and mature study of his region. The concepts which this uses, and to which it is fitted, make a coherent philosophy rooted in a century of Appalachian and wider studies and illustrate well how thought is influenced by environment. The tectonic giants of the European Alps by their very success tempted others too long to view crustal structures and processes in the light of an atypical geosyncline and orogeny. So one can foresee this newly integrated view of the evolution of the American continent exercising a similar tyranny in geological thought. Jargon is fashioned by vivid examples, and the structural units of the American continent or its variety of geosynclines (Kay's terminology suitably translated by King p. 57) have a parochial flavour : thus " ancient rocks, covered by later sediments which remain nearly flat-lying " are *interior lowlands*—interior in the U.S. but not necessarily so. However, the author helps to liberate us from some prevailing fashions. Island arcs have been worked harder on less basis than most concepts and King uses the more general term *tectonic lands* when he needs an area giving rise to sedimentary (and pyroclastic) material. Other prevailing fashions still find their place in his synthesis. Continental drift is considered,

but dismissed for the northern hemisphere at least on the usual somewhat inadequate grounds. This is related to a concept of the earth's crust in terms of *sial* and *sima* overlying the *mafe* (i.e. the peridotite layer) beneath the " Moho ". The first three are chemical concepts and crustal structure, largely deriving from seismic and gravity data, is based on physical properties. It is a pity, when the concept of a paramorphic phase change would seem to give geosynclines and tectonic lands a viable mechanism, to fix the " Moho " as a sima-mafe boundary. In these respects the reviewer feels the author has allowed himself too little room for manoeuvre in the field of crustal evolution.

These are but fascinating undercurrents and overtones in what is a brilliant outline of the structural history of North America. The sequence of the book, after a preliminary " natural history of the continents ", follows respectively the Canadian Shield ; the Interior Lowlands ; the Appalachians, the geosnyclines to the south ; and finally the Cordilleran system with its eastern ranges and plateaux, the main geosyncline, and its late Cenozoic structures. The author had already outlined in more detail the tectonic features of the eastern part of the continent and the present overall synthesis leaves us still wanting more—especially the western part of his more detailed study.

W. B. H.

THE EARTH BENEATH THE SEA. By FRANCIS P. SHEPARD. xii + 275 pp. 113 text-figs. John Hopkins Press, Baltimore, 1959. Price 40*s*.

The author has written a " less technical, but . . . more up to date " book than his *Submarine Geology* (ten years earlier). It is less technical in that references are generally lacking, but it is otherwise most satisfactory since the present state of knowledge is discussed with clarity and economy, avoiding ponderous exposition and pointless detail so often associated with technical writing. The book is effectively illustrated.

Shepard writes with an almost unique authority. As the doyen of modern submarine geologists he is not tempted to make his science seem more impressive than it really is. Essentials are discussed with refreshing frankness, insight, and with the sure touch acquired from a lifetime at sea and in it, much of it with the teams sharing in the recent advances. This book can, then, be recommended without reserve for both general reader and the specialist for it touches profoundly on geological thought whether concerned with the natural history of waves and currents of all sorts, or of beaches, continental shelves, slopes, and ocean floors, and their relevance to the interpretation of sedimentary rocks.

That geologists should not have assumed this or that is a recurring theme throughout, and those who have not professed any particular opinions in sedimentology will be surprised (as well as relieved) to find how little basis there still is for views on many topics. Geologists who have assumed this or that, however, have often been preoccupied with other problems and if the choice was for one kind of investigation as against another, with limited resources, most other fields held more promise. Oceanographical research is only possible by the deployment of enormous resources hitherto available to very few groups. The recent increased tempo in this field parallels that in many others where to ingenuity has been added the expenditure of scores of thousands as against the modest tens and hundreds generally available. The fragmentary nature of the results reminds one of the early progress of continental exploration when for the first time the possibility of travel for the fun of it began to challenge speculation about inaccessible lands long taken for granted. Although many new modes of investigation are in use the oceans are so large that systematic bathymetry and bottom sampling are still the primary needs.

W. B. H.

STRUCTURAL METHODS FOR THE EXPLORATION GEOLOGIST. By PETER C. BADGLEY xv + 280 pp., 328 text-figs. and 10 full page mosaic and overlapping air photographs. Harper and Brothers, New York, 1959 price 60*s*.

SUBSURFACE MAPPING by MARGARET S. BISHOP. ix + 198 pp. and 90 figs. John Wiley and Sons, New York and London, 1960, price 46*s*.

ELEMENTS OF CARTOGRAPHY 2nd Edit. by ARTHUR H. ROBINSON. viii + 343 pp., 233 figs. and many tables. John Wiley and Sons, New York and London, price 70*s*.

These three are each concerned with the practice of some of the great variety of graphical methods for presentation of different aspects of the earth's outer crust, and their many uses.

Elements of Cartography is a second edition of one of the standard works in this field—one which has often tended to be identified with geography. Drawing instruments and their uses are described (Ch. 3) ; chapters 4–6 describe the nature, history, uses, and construction of map projections ; there is a useful chapter (7) on base map compilation and generalization ; chapters 8–11 review the modes of representing data on distribution maps by point, line and area symbols, topographical symbols and so on ; chapters 12–14 refer to design, lettering, and reproduction. There are useful tables, bibliographies and index.

It is as well that the above scope is not further extended to include geological cartography which in its narrower sense has hardly been written about, anyone competent to do so being more than preoccupied practising his science and geological students are not in need of additions to their curriculum. On the other hand geologists should know about maps in general, whether it be the properties of map projections on a larger scale for plotting survey data or for small scale distribution maps. The later chapters too have special relevance in preparation of maps for publication.

Subsurface Mapping at first suggests the activity of a new race of " subsurface geologists ". The latter are found to be ordinary geologists who, because of their training and livelihood at Houston, can do little at the surface except use an enviable amount of subsurface data. Similarly the book is concerned with standard geological mapping methods with an emphasis natural for a University course in Texas. It is a slim handy readable volume covering, in order, (2) contour maps, (3) cross sections, (4) topographic maps, (5) stratigraphic maps, (6) structure maps, (7) isopach maps, (8) facies maps, (9) paleogeographic maps, (10) geophysical and geochemical maps, with introduction and conclusion, good bibliography and index. Jargon inevitably multiplies and while palinspastic and worm's eye maps may be memorable terms because of their classical or modern derivation, one views with some alarm the separation of structural geology and mapping to the extent that dating of diastrophism, and epeirogenic and orogenic movements need to be explained as special subsections. The book is well written and clearly illustrated.

Structural Methods for the Exploration Geologist is the largest of the three books and like the others is entirely to do with graphical methods—i.e. field observations are not explicitly considered. After a brief introduction to the descriptive geometry of attitude, intersection, thickness, and outcrop (ch.l) the sequence leads naturally from the surface via (2) outcrop patterns, (3) cross sections, (4) structure contour maps, (5) isopach and convergence maps, (6) isometric projections, (7) solution of fault problems by descriptive geometry, (8) use of strereographic projections. There is a final chapter on tectonic analysis of specific regions supported by some admirable air photographs. Altogether there is a happy admixture of theory and practice based on wide experience in Canada, the Middle East, and the States. The large format allows the 41 graded exercises to be carried out with minimum time and trouble. This is the most complete practical treatment of the above topics of which the reviewer is aware.

All these books are, of their kind, good and represent a decided advance in their respective fields. Each is concerned with a series of techniques which become sterile unless related to some scientific purpose. In most cases they are acquired by practice and precept ranging over three and more years of scientific education and employment. Hitherto the reviewer has found some difficulty as a teacher in recommending any books to the average student, since those books with sufficient intellectual challenge for an advanced student are too often loaded with laborious elementary explanations, while the elementary things are best taught as skills in class and not as a technology to read and remember. However, in their different ways these three survive this test and are recommended, *Elements of Cartography* and *Subsurface Mapping* for general reading and reference, and *Structural Methods* as a text to precede or accompany an advanced practical course. It follows much the same sequence that the reviewer had found satisfactory.

W. B. H.

NEW INSTRUMENTS AND METHODS OF ENGINEERING GEOLOGY. By N. V. GLAZOV and A. N. GLAZOV, translated by J. P. FITZSIMMONS. pp. 91, text-figs. Consultants Bureau Inc., New York, Chapman and Hall, Ltd., London, 1959. Price 26*s*.

The authors enumerate a number of instruments and methods for the use of soil conservation workers, hydrologists, and civil engineers. Most of these are either redescribed directly from sources outside the Soviet Union, or represent Soviet adaptations and suggestions for adoption, of foreign methods. Many are concerned with the uses of artificial radioactivity and there is a priced list of the available radioactive isotopes. Several ingenious and simple electrical and mechanical instruments are also described. The experienced civil engineer will find himself already familiar with most of the subject matter, while others may prefer more comprehensive textbooks, or original papers.

C. L. F.

GEOLOGY FOR ENGINEERS. By J. M. TREFETHEN. 2nd Edition, pp. viii + 632, numerous text-figs, 12 colour-printed topographical maps. D. van Nostrand Co., London, Princeton, Toronto, 1959. Price 64*s*.

This is described as a textbook for the use of Engineering students, especially civil engineers. The author's plan has been to provide " first, a consideration of the materials of the earths outer portion, their constituents, arrangements, properties, and representation ; next a consideration of the geologic processes that act on the works of man as well as on natural materials ". Unfortunately the presentation is rather verbose and poorly correlated between chapters. Nevertheless, the book does provide much useful information on a variety of topics, though among these the International cloud classification can scarcely be said to have a place in geology.

This second edition differs from the first in some matters of addition, deletion, and rearrangement. Chapter 6, " Mass properties of the Regolith " (elementary soil mechanics) is almost all new. Each chapter has a select bibliography, mostly American.

C. L. F.

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